EVALUATION OF THE MOUNTAIN WAVE FORECAST MODEL'S

STRATOSPHERIC TURBULENCE SIMULATIONS

THESIS

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AFIT/GM/ENP/03-01

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Presented to the Faculty

Department of Engineering Physics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Meteorology

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March 2003

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Approved:

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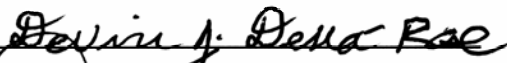<tr><td>_____</td><td>5 MAR 03</td></tr>
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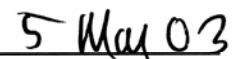<tr><td>Devin J. Della-Rose (Member)</td><td>Date</td></tr>
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Abstract

Stratospheric turbulence (Stratoturb) is a well-known hazard to aircraft in flight. Forecasting mountain waves, specifically the breaking of these waves, is necessary to accurately predict the presence of Stratoturb. The Air Force Weather Agency (AFWA) requested a product with the capability of forecasting Stratoturb at 30, 50, and 70 mb using model data currently available. To facilitate their request, the Mountain Wave Forecast Model (MWFM) was acquired from the Naval Research Laboratory.

MWFM turbulence forecasts generated twice daily over East Asia, using the AVN and MM5 models for initialization, were compared to 'S' layer turbulence analyses from the Rawinsonde Observation (RAOB) program, currently used operationally to warn aircrews. Actual verification of the MWFM forecasts was unachievable since in situ turbulence observations were not available, and as a result only subjective assessments of the MWFM's capabilities were possible.

The MWFM was determined to be the superior forecast tool based on the temporal and spatial coverage provided when compared to RAOB as well as its promising ability to alleviate the reported overforecasting inherent to the RAOB analyses. Therefore, the MWFM, including code modifications made at AFIT, was recommended for use by AFWA. Further objective analysis of the model's accuracy should be conducted.

EVALUATION OF THE MOUNTAIN WAVE FORECAST MODEL'S

STRATOSPHERIC TURBULENCE SIMULATIONS

I. Introduction

The Department of Defense (DoD) and the Air Force are continuing to expand

their operations into the stratospheric region of the atmosphere. Perhaps the most

important Air Force stratospheric mission is reconnaissance. These flights provide

invaluable intelligence to the warfighter as well as information for peacetime operations.

The Air Force employs manned aircraft, such as the U-2, and unmanned aerial vehicles

(UAV) like the Global Hawk to accomplish these high altitude missions. As a result,

protection of these valuable assets from dangerous atmospheric conditions is becoming

an increasing concern for the Air Force and the DoD.

Stratospheric turbulence (Stratoturb) is a long-standing concern for U-2

operations and is now threatening actions involving UAV aircraft. Pilots describe

Stratoturb as a roller coaster ride that can cause virtually instantaneous drops in altitude

in excess of hundreds of feet. Stratoturb has been responsible for multiple U-2 mishaps

resulting in emergency landings, loss of aircraft, and in one case the death of the pilot

(ACC Memo 2002).

The presence of stratospheric turbulence is well correlated with areas of

horizontal temperature variations along the flight path (Waco 1972). Wind flow over

terrain on the earth's surface is a contributing cause of the strong temperature gradients

(Waco 1972). The flow over terrain forces a vertical displacement of air parcels that may

then experience a buoyant oscillation in a stably stratified atmosphere. These oscillations are influenced by the restoring forces of buoyancy and gravity and are frequently termed "gravity waves". When forced by mountainous terrain, they may also be referred to as "mountain waves" or "lee waves" (Glickman et al. 2000). The energy of the waves can be transferred to the surrounding atmosphere in the form of turbulence. The ability to forecast the movement of mountain waves as they propagate both vertically above the forcing terrain and downwind from the terrain is invaluable to the prediction of turbulence in the upper troposphere and lower stratosphere.

At this time, the Air Force Weather Agency (AFWA) has no automated means of predicting turbulence at stratospheric altitudes. The methods currently used to provide forecasts to operational units are a subjective assessment of the synoptic scale conditions as well as a subjective analysis of temperature and winds using data from the National Center for Environmental Prediction's (NCEP) global Aviation (AVN) Model. The turbulence algorithm employed by AFWA uses data from the Fifth Generation Pennsylvania State University (PSU)/National Center for Atmospheric Research's (NCAR) Mesoscale Model (MM5) and diagnoses turbulence based on vertical wind shear and deformation and convergence of the wind (Ellrod and Knapp 1992). The algorithm is not used at levels desired for operations within the stratosphere and does not take into account the effects of atmospheric gravity waves. Operational units may provide nowcasts of turbulent conditions using the latest atmospheric rawinsonde sounding, which will be discussed in Chapter 2.

One of the most active Stratoturb locations on the earth is located over East Asia. The increased activity is due mainly to the rugged terrain features located in this region

and very active synoptic conditions, especially during the winter. Due to the large DoD presence in this region of the world, the need to successfully and safely collect intelligence and conduct other vital operations is essential. Therefore, AFWA must be able to provide accurate and timely forecasts to the flying units in this theater of operations.

1.1 Statement of the Problem

AFWA is requesting a product that will provide an automated means of predicting Stratoturb using output from Numerical Weather Prediction (NWP) models that are already available. Specifically, AFWA wants Stratoturb forecasts at the 30, 50, and 70 mb levels. Currently, NWP output available at AFWA includes data from NCEP's AVN and AFWA's MM5. The AVN model currently provides forecast data into the stratosphere up to and including 10 mb. At the time of this writing, the Air Force's MM5 is configured to extend up to only 59 mb (Wegiel 2002). As a result, the MM5 must be reconfigured to provide output encompassing the desired forecast levels. Both of these models supply forecasts out to 72 hours, with the AVN extending beyond ten days.

To fulfill AFWA's request, the Mountain Wave Forecast Model (MWFM) was acquired from the Naval Research Laboratory (NRL). The model was provided by the NRL in two versions. The MWFM is a model that forecasts the development and propagation of terrain-induced gravity waves, based on an atmospheric profile developed from large-scale NWP model output and a terrain database. Post-processed data provided

by the AVN and MM5 models are used as input for the MWFM. The MWFM algorithm and turbulence forecasting procedures are described in detail in Chapter 2.

1.2 Research Objectives

The ultimate outcome of this research is to provide a recommendation to AFWA on the effectiveness of the MWFM and its feasibility for use as an operational forecast tool. The specific goals of this research are as follows:

1. Compile and run the MWFM using output data from NCEP's AVN model

2. Reconfigure the MM5 to raise the pressure top to 10 mb and produce the model runs over the desired geographic domain

3. Run the MWFM using output data from the reconfigured MM5

4. Develop and execute a verification procedure for MWFM forecasts

5. Refine the NRL preliminary MWFM turbulence intensity scale (described in Section 1.3)

1.3 Research Approach

The model output from the AVN and MM5 models used as input to the MWFM is required to develop atmospheric profiles of wind speed and direction, density and stability. Once a profile is derived, the MWFM produces a forecast of mountain wave activity, tracks the wave propagation, and diagnoses associated turbulence. The forecasts produced by the MWFM must be verified in order to judge the model's effectiveness.

The results of the verification can then be used as the basis for a recommendation to AFWA.

Ultimately, the best verification procedure for turbulence forecasts involves the use of real-time stratospheric pilot reports of turbulence. Exhaustive efforts were put forth to achieve this ideal goal. Unfortunately, the nature of military operations often limits the flow of sensitive information. In order to maintain the security and safety of operations, in situ pilot reports were not made available for use as verification during this research.

In lieu of verification based on pilot reports, the forecasts produced are compared to Stratoturb analyses based on rawinsonde balloon observations. These Stratoturb nowcasts are regularly used by operational units in the area of interest and are produced by the Rawinsonde Observation (RAOB) program version 5.2, discussed in Chapter 2. Weather forecasters currently provide the RAOB Stratoturb analyses to the flying units in support of U-2 reconnaissance operations. The RAOB analyses, as described by an operational flying unit in Eastern Asia, display a tendency to overstate the presence and intensity of Stratoturb. Apparent proof of the inclination of the RAOB product to overanalyze Stratoturb is seen during the comparisons of the MWFM forecasts and RAOB analyses described in Chapter 4. The implications of the RAOB overanalysis in regard to its use as a Stratoturb forecast tool are discussed in Chapter 5.

The tests of the MWFM Stratoturb forecasts compared to the RAOB analyses are separated to determine how the two MWFM versions, the two NWP sources, and their combinations differ. The comparison of the turbulence forecasts to the RAOB analyses provides insight into the MWFM's performance versus an operationally used Stratoturb

product. The comparison procedures are discussed in detail in Chapter 3. Chapter 5 provides a discussion of the various comparisons and discusses recommendations concerning the Air Force's use of the MWFM as a means of forecasting Stratoturb.

The turbulence forecasts produced by the MWFM are provided in units that are not easily translated to turbulence intensity. Therefore, the developers of the MWFM created a preliminary turbulence intensity scale based on reports provided by National Aeronautics and Space Administration (NASA) ER-2 flights. Since the MWFM forecasts are not being compared against true turbulence observations, a refinement of the NRL's turbulence intensity scale was not pursued.

Due to the extreme amount of mountain wave activity over East Asia and the large DoD presence, the forecasts are confined to this region, specifically the Republic of Korea (ROK) and Japan. The reporting stations for the rawinsonde balloon soundings used with the RAOB program for comparison with the MWFM are located in these two countries. The specific stations and their respective locations are listed in Chapter 3.

II. Literature Review

2.1 Gravity Waves and Mountain Waves

Gravity waves are defined as a wave disturbance in which buoyancy acts as the restoring force on a parcel displaced from hydrostatic equilibrium (Glickman et al. 2002). They may also be referred to as buoyancy waves. These waves play a large role in the global atmospheric circulation, to include transporting significant amounts of energy and momentum within the troposphere as well as the upper atmosphere, and have been attributed with influencing the global mean wind flow in the middle atmosphere (McFarlane 1987). Gravity waves can be excited in a number of ways, including wind flow over topography, shear instability, and deep convection. The effects of gravity waves are often hazardous to military operations. They are known to produce clear air turbulence (CAT), severe down slope windstorms on the lee of mountains, and they can trigger convective activity (Durran 1986, Hooke 1986).

Since gravity waves have such threatening potential, it is necessary to understand how they form and propagate within the atmosphere. Buoyancy waves can form in a statically stable atmosphere when some mechanism, either shear instability or some external forcing, displaces a parcel of air vertically. If the parcel ascends too quickly, the air within does not have time to achieve pressure equilibrium with its surroundings. This unequal state is then communicated to the surrounding atmosphere as a spectrum of sound waves, similar to a lightning flash and thunder, and no gravity wave is produced. If displaced too slowly, pressure equilibrium is maintained as well as thermal

equilibrium. A parcel in thermal equilibrium with its surroundings will maintain neutral buoyancy. Finally, if the parcel is raised at a speed in which pressure equilibrium is maintained and thermal equilibrium is not, the parcel will be buoyant (Hooke 1986).

Whether or not a buoyant parcel will rise or sink is dependent on the stability of the surrounding atmosphere. In an unstable environment, a parcel displaced vertically to some new level will be warmer than its surroundings. In this situation, the parcel will continue to rise until it reaches an area in which the surrounding air is warmer or it achieves thermal equilibrium through adiabatic cooling. In a stably stratified atmosphere, the displaced parcel will be colder than its new environment, and its rate of ascent slows until it reverses direction and begins to sink. The kinetic energy of the sinking parcel will not allow it to stop once it reaches its origin level, but instead it continues to descend and adiabatically warm. As the parcel becomes warmer than its surroundings, its descent will slow and eventually stop. At this time, the parcel will begin to ascend once again only to continue the process until dissipative forces remove sufficient energy from the parcel to allow it to come to rest (Hooke 1986).

The oscillation of the parcel about its origin level has a predictable frequency due to the nearly constant gravitational force. This frequency is called the Brunt-Väisälä frequency (N) and is defined as:

$$N^2 = \frac{g}{\theta_0}\left(\frac{d}{dz}\theta_0\right) \tag{1}$$

where g is the acceleration due to gravity, θ_0 is the potential temperature of the environment, and $\frac{d}{dz}\theta_0$ is a measure of the atmospheric stability. The frequency increases as the atmospheric stability increases.

One of the forces exerted by gravity waves on the atmosphere is gravity wave drag. Glickman et al. (2000) define gravity wave drag as a zonal acceleration produced by upward propagating gravity waves at levels where the waves break. The decrease in atmospheric density with height allows the amplitude of vertically propagating waves to increase. When the wave amplitudes become too large, the waves break. Atmospheric waves are a major transporter of energy and momentum, and the breaking waves transfer this energy to the surrounding atmosphere (Lindzen 1990).

Mountain waves are externally forced gravity waves generated by airflow over a mountain or terrain barrier. Terrain features are a primary initiator of gravity waves and therefore play a large role in the transfer of energy within the atmosphere. The shape of the terrain and the atmospheric structure largely influence the nature of the waves produced. There are two categories of mountain waves (Glickman et al. 2000). First, there are vertically propagating waves. Vertically propagating waves remain stationary above the initiating terrain feature. These waves have wavelengths of tens of kilometers and can travel into the lower stratosphere. They are capable of producing severe CAT as well as devastating down slope winds. The second type of mountain wave is the trapped lee wave. These waves develop beneath a layer of large static stability and propagate downstream from the forcing terrain. As they progress, they deposit turbulent energy farther from the mountain than the vertically propagating waves. It is possible to have both vertically propagating and trapped waves in the same environment. Also, trapped lee waves may not be completely trapped beneath the stable layer. These "leaky" waves transport energy both vertically and downwind from the forcing terrain (Glickman et al. 2000).

Once an understanding of the basics of formation and propagation of mountain waves is achieved, it is profitable to develop a means of forecasting their development and progression. Classically, this is done using linear perturbation theory to describe the complex spectra of wave generation. Although much effort is going towards modeling the nonlinear aspects of mountain waves, the linear theory can provide valuable insights into the nature of the waves and does an adequate job of describing these highly complicated processes (Geller et al. 1975, McFarlane 1987). A summary of the linear concepts is presented in the next section.

2.2 Mountain Wave Forecasts

Forecasting the effects of mountain waves is often done using a parameterization within a global or mesoscale NWP model since the horizontal wavelength of the waves is generally smaller than the model can resolve. The parameterization frequently used is a gravity wave drag scheme. In the simplest terms, forecasting mountain wave activity involves using linearized equations of motion to predict the production of waves over a specified terrain shape for a known atmospheric stability profile. The governing equations can be assumed to be hydrostatic or non-hydrostatic, but are taken to be two-dimensional in linear perturbation theory. The decision to use either hydrostatic or non-hydrostatic equations plays a large role in the vertical and horizontal extent of propagation of the waves. It has been shown that the non-hydrostatic assumption may be the best for predicting the intensity of the mountain waves as well as the vertical and horizontal extent (Keller 1994). When using linear theory to describe waves, the most

common form of the equations involves the assumption of a hydrostatic atmosphere due to the relative simplicity.

The two-dimensional assumption in the model implies the length of the ridgeline is large compared to its width. This has been shown to be a valid assumption in many situations (Keller 1994), although narrower ridgelines will produce mountain waves with more three-dimensional features (NRL 2001). The hydrostatic assumption implies that the width of "each ridge is broad compared to an intrinsic, flow-related vertical wave-length" (NRL 2001). For ranges much greater than 10 km in width, this assumption is typically a valid approximation (NRL 2001). The hydrostatic or broad ridge assumption also has the property of confining the mountain waves to the vertically propagating type (Holton 1992). This property may lead to discrepancies when the atmosphere and terrain are conducive to producing trapped or "leaky" waves that propagate farther downstream.

According to linear theory, the amplitude of a two-dimensional hydrostatic wave can be expressed as a function of an atmospheric level's mean flow, stability, and density, which are assumed to vary slowly with height. Typically, the amplitude of the wave will increase with height as density decreases. The propagation of the mountain wave is expressed as a ratio of induced vertical displacement or amplitude at the initial level to the vertical displacement at a next higher level:

$$\frac{D(z+\Delta z)}{D(z)} = \left[\frac{\rho(z)N(z)U_{\perp}(z)}{\rho(z+\Delta z)N(z+\Delta z)U_{\perp}(z+\Delta z)}\right]^{\frac{1}{2}} \qquad (2)$$

where D is the wave induced vertical displacement or amplitude, ρ is the density, N is the Brunt-Väisälä frequency, and $U_{\perp}$ is the perpendicular wind component (Bacmeister et al. 1994). If the initial displacement, $D(z)$, is known, this ratio can then be used to

determine the displacement at the next level, $D(z + \Delta z)$. This process is then repeated with the previously calculated level used to derive the displacement at the next higher level (Bacmeister et al. 1994).

The initial amplitude of the wave is normally given the value of the effective height of the topography. The effective height is chosen to be the minimum between a value proportional to the model terrain height and an atmosphere specific saturation limit. The saturation limit (S) is defined as the ratio of the perpendicular wind component ($U_\perp$) to stability (N) at the mountaintop level,

$$S(z) \equiv \frac{U_\perp(z)}{N(z)} \tag{3}$$

and this formula is used to diagnose the wave breaking potential at the initial height (Bacmeister et al. 1994). By taking the minimum between the effective height and the initial saturation limit, the effect of blocking is taken into account. Blocking occurs when the terrain feature "blocks" the stably stratified air mass on the windward side of the feature. The air flowing over this blocked air mass and across the terrain will sense an effective height proportional to the distance from the top of the air mass to the mountaintop (Whiteman 2000). Blocking effectively reduces the height of the terrain and limits the amplitude of any mountain waves produced (McFarlane 1987).

The mountain waves generated transport the horizontal momentum of the background wind flow vertically. The redistribution of horizontal momentum in the vertical is known as momentum flux and has units of stress, Nm^{-2} (Glickman et al. 2002). The wave's momentum flux has been shown to be a conservative property during linear wave propagation as long as wave breaking does not occur (Eliassen and Palm 1960). According to Lindzen (1990), "in the absence of damping, local thermal forcing, and

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critical (saturation) levels, no momentum flux is deposited or extracted from the basic flow."

The potential for wave breaking at levels above the mountaintop is calculated using the saturation limit (3) as before. When the amplitude for each subsequent level is calculated, the saturation limit for that level is also calculated. The saturation limit represents the maximum amplitude the wave can attain at a specific level. If the calculated amplitude is greater than the saturation limit, the saturation limit is taken as the new amplitude. If the wave amplitude has been limited due to saturation, the momentum flux of the wave has been reduced. It is assumed that turbulence is generated whenever wave saturation is invoked. Also, the amount by which the momentum flux must decrease to reduce the amplitude of the wave to the saturation limit is assumed to be proportional to the turbulence intensity (Bacmeister et al. 1994). The turbulence or stress imparted to the layer (between calculation levels) is described by,

$$Turb\left(z + \tfrac{\Delta z}{2}\right) \propto \phi(z) - \phi(z + \Delta z) \tag{4}$$

where ϕ represents the momentum flux.

Forecasts of mountain wave activity are being produced by several organizations, using both hydrostatic and non-hydrostatic numerical simulations. These models, which are typically centered over terrain features, are not used on a global scale and are initialized using temperature and wind forecasts generated by coarser resolution global models, such as the AVN. The method used by the NRL's MWFM to predict mountain waves, associated turbulence, and its terrain representation is discussed below.

2.3 The Mountain Wave Forecast Model

The NRL developed the MWFM as a means of predicting gravity wave activity in mountainous regions, and it is currently being used in areas of atmospheric research beyond Stratoturb applications. The NRL has been running the original version, MWFM 1.1, for over seven years, and they are also running a newer version, MWFM 2.1, simultaneously. The MWFM 2.1 has been in operation for nearly three years (Eckermann 2002). To construct forecasts, the MWFM currently has the capability to ingest atmospheric variable data from multiple sources, including NCEP's AVN model output in Gridded Binary (GRIB) format.

The terrain over which the mountain wave develops plays an important role. The MWFM uses a terrain database developed by Bacmeister et al. (1994), and both the MWFM 1.1 and 2.1 currently use the same terrain map. The terrain database was derived from a global dataset provided by the National Center for Atmospheric Research and is comprised of mean elevations within a 10' X 10' area (Bacmeister et al. 1994). The topography data are then interpolated onto a 5' X 5' grid. The interpolated 5' X 5' mean elevation data are then used to produce a ridge database containing a list of two-dimensional ridges and each ridges associated "cross-ridge width, height, and horizontal orientation of its long axis (Eckermann et al. 2001)." These ridge features govern the type of wave produced by the general flow over the feature. NRL is planning to update the current ridge database (Eckermann 2002).

2.3.1 MWFM Version 1.1. The MWFM 1.1 is a two-dimensional hydrostatic gravity

wave model. The model produces turbulence forecasts based on the deposition of a

wave's momentum flux, as described by the linear theory above. The momentum flux

deposition values, in units of Jm^{-3}, have been subjectively scaled by the NRL to express

turbulence intensity levels as described earlier. A drawback of MWFM 1.1 lies in its use

of the hydrostatic assumption. The hydrostatic assumption implies each ridge has a broad

cross-ridge width. This assumption leads to over-forecasting the intensity of the

mountain waves directly over narrow ridgelines, which should produce evanescent waves

(Holton 1992), and under-forecasting intensity downstream, as waves are limited to the

vertically propagating type (NRL 2001, Eckermann et al. 2001). When dealing with

flight crew and aircraft safety, this limitation has not been viewed as a hindrance to

operations since it is typically better to err on the side of caution (Eckermann et al. 2001).

2.3.2 MWFM Version 2.1. MWFM 2.1 is an enhanced version of the MWFM, which

takes into account three-dimensional, non-hydrostatic effects on gravity waves. This

version of the MWFM employs three-dimensional ray-tracing techniques, the specifics of

which are described in detail by Marks and Eckermann (1995). The ray-tracing aspect of

the model allows for better prediction of waves produced by mountain ranges that display

a more three-dimensional nature, such as an isolated peak (NRL 2001, Eckermann 2002).

Ray tracing permits the diagnosis of reflected or trapped waves and prevents some

vertical propagation of the waves (Eckermann et al. 2001). MWFM 2.1 identifies the

presence of reflected rays and discontinues the ray after reflection has occurred

(Eckermann et al. 2001). These reflected rays do not reach the stratosphere and therefore

play no role in Stratoturb production. The ray tracing technique is an improvement over

MWFM 1.1, which allows all non-breaking waves to reach the stratosphere and over

estimates the Stratoturb intensities.

A ray, as defined by Andrews et al. (1987), is "the trajectory of a point moving

with the local group velocity." Basically, a wave packet is tracked as is moves according

to the group velocity of the wave. Ray paths are followed using so-called ray-tracing

equations. These equations give the variation in wavenumber and position along the path

of the ray (Andrews et al. 1987). In order to use the ray tracing technique, atmospheric

properties, such as zonal velocity and stability, are assumed to vary slowly with height

(Gill 1982). Therefore, the Wentzel-Kramers-Brillouin-Jeffreys (WKBJ) approximation

is employed. According to Gill (1982), under the WKBJ approximation, zonal velocity

and stability are the only contributing factors to changes in the wave properties.

Due to the complexity of calculating the changes in wave amplitude along a ray,

MWFM 2.1 employs a simpler ray-tracing technique that provides "backwards

compatibility" with the MWFM 1.1 (Eckermann et al. 2001). The amplitude of the wave

is computed assuming the vertical flux of wave action density remains constant for

individual rays when dissipative effects are absent (Eckermann et al. 2001). The vertical

flux of wave action density, F, is represented by:

$$F = c_{gz} A \tag{5}$$

where A is the wave action density and c_{gz} is the vertical group velocity (Marks and

Eckermann 1995). As the ray tracing equations are integrated along the trajectory of the

ray, the time derivative of (5) is also integrated to find subsequent values of F, and

therefore changes in A (Marks and Eckermann 1995). The change in wave action and

the corresponding change in wave energy is then used to find the of wave amplitude (Andrews et al. 1987). The variation in amplitude between levels is then known, and the standard saturation theory used in MWFM 1.1 is employed to calculate wave breaking and momentum flux deposition (Eckermann et al. 2001).

MWFM 2.1 is designed to initiate a user-defined number of rays from each ridge in the domain. Also, the user may define the number of horizontal wavelengths launched. The standard forecast is performed using 18 rays at two, ridge specific wavelengths at equally spaced azimuths between 0 and 180° on the leeward side of the ridge. The ridge specific wavelengths are calculated based on the cross-ridge width and vary for each ridge. During operational applications, the user must balance the increased calculation time imposed by raising the number of rays launched from each ridge with the increase in resolution provided.

The amplitudes of waves associated with the multiple rays initiated by a ridge are dependent on the fit of the ridge to a two-dimensional standard, with the length of the ridge large compared to the cross-ridge width. Ridges that fit the two-dimensional standard well initiate rays where the largest amplitudes are assigned to rays that are closest to being perpendicular to the ridge, pictured in Figure 1. This produces wave forecasts similar to those generated by MWFM 1.1. Ridges that are more three-dimensional in nature, such as an isolated peak, are known to produce wave patterns resembling a ship-wake. Waves originating from three-dimensional features exhibit comparable initial amplitudes at all azimuths, shown in Figure 2.

MWFM 2.1 also uses two additional simple adjustments in its calculations to account for the effects of friction and blocking. With flow over topography, friction

slows the mean wind and wave amplitudes are reduced. MWFM 2.1 accounts for the

frictional effects by arbitrarily scaling down the initial amplitude of waves. Blocking

effects, discussed previously, are estimated by calculating the local Froude number (Fr),

$$Fr = \frac{U_\perp}{Nh} \tag{6}$$

where $U_\perp$ is the ridge perpendicular wind speed, N is the Brunt-Väisälä frequency, and

h is the height of the terrain. The Froude number is as the ratio of the kinetic energy of

the flow to the potential energy and is valuable in diagnosing the stability of the upstream

environment. If blocking effects are important, when $Fr \sim O(1)$, the effective height of

the terrain and the amplitude of the waves are reduced (Eckermann 2002).
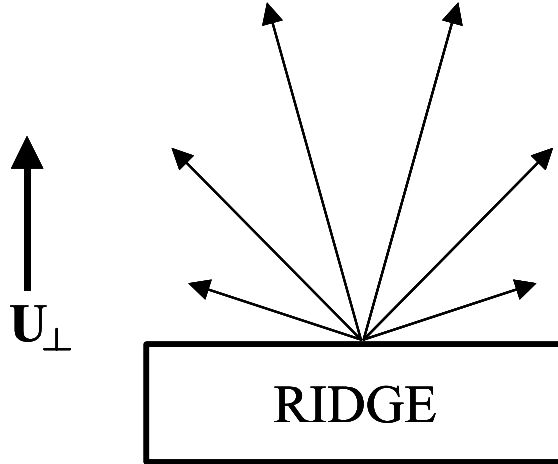
Figure 1. Rays Launched from a Quasi-Two-Dimensional Ridge. An example of six
rays launched from a single, quasi-two-dimensional ridge. The length of each ray is
proportional to the initial amplitude of the wave produced by the ridge, with the largest
amplitude assigned to rays nearly orthogonal to the ridge. A ridge fitting the ideal, two-
dimensional standard will launch a single ray perpendicular to the ridge.
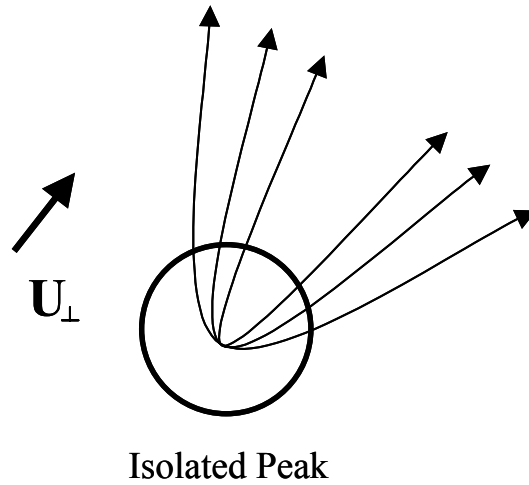
Isolated Peak

Figure 2. Rays Launched from an Isolated Peak. An example of six rays initiated over a single, isolated (three-dimensional) peak. The length of the rays is proportional to the initial amplitude of the wave produced by the ridge. The three-dimensional characteristic of the mountain produces waves with nearly equal beginning amplitudes. Mountain waves from a ridge of this shape exhibit a ship-wake pattern.

2.4 Numerical Weather Prediction (NWP) Models Used

2.4.1 NCEP AVN Model. NCEP has been running a combination of the AVN and

Medium-Range Forecast Model (MRF) since the 1980's. In April 2002, they

discontinued use of the MRF in favor of the AVN. The AVN is a spectral model with

spherical harmonic basis functions. The model is run over a global domain, and the

topographical database used by the AVN is a 10' X 10' resolution data set provided by

the U.S. Navy. AVN forecasts are available from 0-384 hours (analysis to 16 days).

Data is accessible at the NCEP FTP site, and datasets are available in three-hour

increments out to 204 hours and 12-hour increments after that (NCEP 2002).

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The model's resolutions, horizontal, vertical and temporal, vary throughout the run. For the first 84 hours, the horizontal resolution is T170. T170 resolution corresponds to approximately 2.1° of longitude per wave. After 86 hours, horizontal resolution is decreased to T126 or nearly 3° of longitude per wave. Then resolution is decreased again at 168 hours to T62. At T62 horizontal resolution, a wave encompasses approximately 5.8° of longitude. The temporal resolution changes at the same time the horizontal resolution changes. Initially, the AVN performs computations in 9-minute time steps. At 96 hours, the time step increases to 18 minutes, and then increases to 24 minutes at 168 hours (NCEP 2002).

The vertical resolution of the AVN is changed only once during the model run. From the analysis time out to 84 hours, the AVN uses 42 unevenly distributed sigma levels. Typically, 12 sigma levels are positioned below 800 mb and 10 levels are above 100 mb. After the 84-hour point, the number of sigma levels is decreased to 28, and this configuration is maintained throughout the remainder of the model run. The atmospheric column represented by these sigma level configurations extends from the surface up to approximately 2 mb (NCEP 2002).

The AVN is run at the NCEP Central Operations office in Camp Springs, Maryland on an IBM RS/6000 SP (Class VIII) computer in an AIX operating environment. The model is run four times daily at 00, 06, 12, and 18 Zulu (Z), out to 384 hours. The vertical extent of the model, up to 2 mb, renders it an exploitable source of input data for the MWFM (NCEP 2002).

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2.4.2 MM5 Model. The Air Force's primary numerical weather prediction model is the

MM5, first developed at Pennsylvania State University in 1971. The MM5 is a three-

dimensional, non-hydrostatic, finite-difference, primitive-equation, grid point model. It

has undergone many changes in its lifetime, and the third version of the fifth generation

of the model (MM5v3) is used during this research. MM5 is highly flexible, allowing

users to define areas of coverage and to nest areas within a parent domain. The MM5 is

operationally used by AFWA at 29 locations around the globe, including outer and nested

domains, with 45 km and 15 km resolutions available. It also provides the option of

various physical parameterization packages from which the user can choose (Grell et al.

1995).

The MM5 uses the sigma coordinate system as its vertical coordinate, defined

according to Dudhia et al. (2001). The number of sigma levels defines the vertical

resolution of the model, and AFWA's MM5 uses 41 sigma levels. The horizontal grid of

the MM5 uses an Arakawa-Lamb B-staggering of atmospheric variables. Scalars, such as

temperature, are defined at the center of a grid box, while horizontal and vertical

components of the wind velocity are defined at the corners of the grid boxes (Dudhia et

al. 2001). The spacing of the grid points determines the horizontal resolution of the

model.

The main inadequacy of AFWA's configuration of the MM5 for prediction of

stratospheric turbulence is the pressure cap or upper bound of the model. At this time,

the model is capped at 59 mb (Wegiel 2002). The MM5 does allow the user to define the

upper limit of the model. Once the new upper limit is defined the user can either add new

sigma levels or redistribute the existing sigma levels within the expanded pressure domain to adjust the vertical resolution.
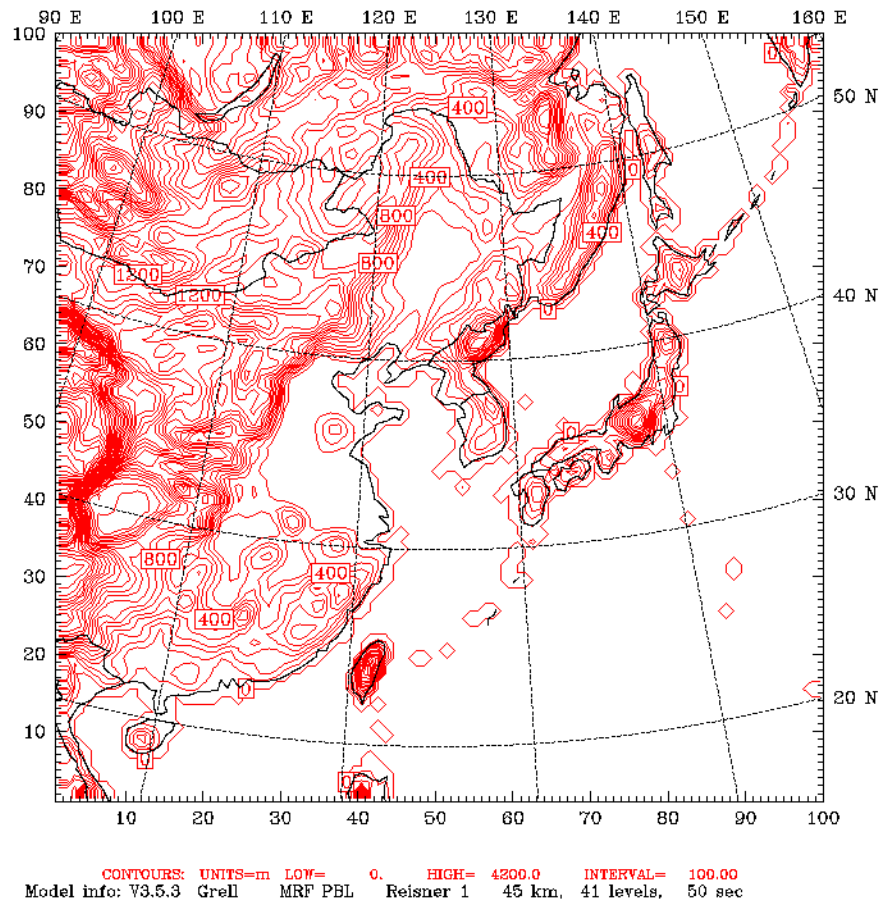
Figure 3. East Asian domain used with AFIT MM5. Contouring in meters indicates the placement and elevations of terrain features.

The weather lab at the Air Force Institute of Technology (AFIT) is currently running the MM5 in a configuration similar to AFWA over a much more limited geographical area. The domain used for AFIT MM5 forecasts is pictured in Figure 3. In the course of this research, the pressure top of the MM5 at AFIT has been raised to 10 mb. The reconfigured model maintains the use of 41 sigma levels that are redistributed to

provide greater resolution above 100 mb. Table 1 presents a list of the sigma level values

used during this research.

Table 1. AFIT MM5 Sigma Level List

Sigma level values range between 0 (model top) and 1 (surface).							
1.000	0.995	0.992	0.983	0.975	0.961	0.949	0.932
0.917	0.897	0.878	0.855	0.832	0.806	0.778	0.749
0.718	0.687	0.654	0.623	0.590	0.559	0.526	0.495
0.462	0.431	0.398	0.367	0.334	0.304	0.272	0.244
0.213	0.187	0.158	0.134	0.107	0.060	0.030	0.010
0.002	0.000						

The MM5 at AFIT is initialized using AVN GRIB data and is run out to 60 hours

with output data available in three-hour increments. AFIT MM5 runs are done on a Sun

Solaris 8.0 computer in a SunOS/UNIX environment. The runs are performed using

MPICH, a message-passing interface, which allows the use of multiple processors. With

the increased pressure top, data from AFIT MM5 runs are available for use as input to the

MWFM. Preparing the MM5 output data for use by the MWFM is discussed in detail in

Chapter 3.

2.5 RAOB Program Details

Environmental Research Services developed the RAOB program as a

visualization and analysis tool for rawinsonde balloon soundings. The program is

capable of ingesting rawinsonde and radiosonde data in multiple formats. Once read, the

data are used to generate sounding diagrams, such as the Skew-T diagram. RAOB also

calculates numerous atmospheric parameters to include turbulence, icing, stability

indices, and severe weather analyses. The latest version available for use during this

research is RAOB 5.2, and it includes a HiCAT (High Altitude CAT) analysis module to diagnose the presence of high altitude turbulence. The analysis method used by the HiCAT module to identify the existence of turbulence is discussed below.

The RAOB HiCAT analysis of turbulence is performed using a slight modification of the 'S' layer conceptual model developed by Sinclair and Kuhn (1991). The 'S' layer is comprised of three distinct layers in the atmosphere: two inversions and a mixing layer. The layers are arranged in such a way as to resemble an 'S' in the temperature sounding trace (Figure 4). Using data provided by the Air Force's HICAT research initiative conducted in the mid 1960's, Sinclair and Kuhn (1991) showed that the 'S' layer model had a hit rate of 93.8%. Also, their research was able to determine that 100% of the turbulence was confined to the mixing layer portion of the 'S' layer, where the inversions act to contain the turbulent mixing and minimize the escape of this energy to the surrounding atmosphere. It is important to note that although the 'S' layer approach verified well with the HICAT data, no objective verification has been performed on this technique since that time. The implementation of the 'S' layer model by the RAOB program has not been objectively verified either.

Once an 'S' layer is identified, the layer is analyzed to determine the lapse rate of the mixing layer, the depth of the 'S' layer, and the 'S' layer vertical temperature difference. These features are then used to compute a combined 'S' Layer Advance Turbulence (SLAT) factor, which is used to determine the intensity of turbulence present in the mixing layer. The turbulence intensity is directly related to the mixing layer temperature lapse rate and the vertical temperature difference, while intensity is inversely related to the depth of the 'S' layer (Sinclair and Kuhn 1991).

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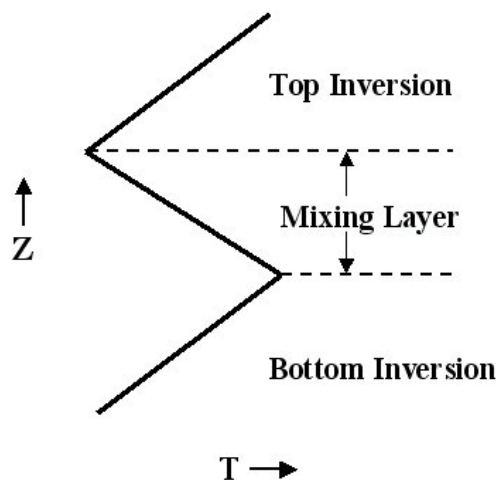
Figure 4. The 'S' Layer Model. The model, used to diagnose the presence of turbulence, looks for three distinct layers found in the rawinsonde temperature trace. Turbulence has been highly correlated with the mixing layer. Modified from Sinclair and Kuhn (1991).

The operational units in need of Stratoturb forecasts within the target region employ the RAOB program for pilot briefings. RAOB is considered their "first option" in determining the presence of Stratoturb when briefing flight crews (McQuoid 2002). Since RAOB uses the most recent sounding data, the turbulence analysis is actually a hindcast. RAOB has the capability to ingest forecast soundings based on model output, but the lack of these forecast products over East Asia often rules out this alternative. The forecaster has the option of modifying the most recent sounding within the RAOB program to reflect expected changes to the atmospheric column. However, this is a time consuming process and will ultimately lead to increased errors as the forecaster tries to predict conditions farther into the future.

III. Methodology

3.1 Overview

One of the goals of this research is to verify the reliability of the Stratoturb forecasts produced by the MWFM. Since operational units currently use the RAOB HiCAT output as their primary Stratoturb tool, the MWFM turbulence forecasts are compared to the RAOB diagnoses. The comparison of the two products will provide an understanding of the effectiveness of the MWFM versus a current, operationally used product. To meet these ends, the RAOB diagnoses are considered observations of turbulence for purposes of analysis. Unfortunately, the analyses do not provide an actual measurement of turbulence and cannot be used for actual verification of the turbulence forecasts, which would require in situ observations.

The forecasts are centered over Eastern Asia due mainly to the large amount of Stratoturb activity and the considerable DoD presence in this part of the world. Data used for comparison are taken from rawinsonde balloon flights originating in the ROK and Japan. The varying terrain of these countries is highly conducive to the formation of mountain waves especially when taken with the strong winds present in this region of the globe. The forecast period includes the dates from November 4, 2002 to December 4, 2002. The period runs through the late Fall season in the Northern Hemisphere when Stratoturb activity is increasing due to the southward migration of strong jet stream winds over the region.

3.2 Data

3.2.1 MWFM Input Data. The MWFM parameterization requires data from a larger scale

NWP model to make the forecasts. These model output data fields are used to create the

atmospheric profiles of wind speed, wind direction, density, and stability needed to make

the wave forecasts. Each of these parameters is needed throughout the height of the

column up to a level above the highest mountain wave plot desired. The MWFM

requires the following four input fields from the larger domain model:

1. Absolute Temperature

2. Geopotential Height

3. Zonal Component of the Wind

4. Meridional Component of the Wind

The MWFM was provided to AFIT with the capability of ingesting data from the

NCEP AVN model, the Data Assimilation Office model data, the Navy Operational

Global Atmospheric Prediction System model, and other NRL empirical models.

Modifications to the MWFM data ingesting routines made at AFIT included adding the

capability to ingest MM5 GRIB data.

3.2.2 AVN Input Data. The AVN data used as input to the MWFM were downloaded

from the NCEP FTP site. The MWFM is designed to automatically retrieve the

necessary files from the FTP site during the model run, or it will use the files if they are

already stored locally. When doing a mountain wave forecast, the MWFM uses or FTPs

only the file it needs for the time it is currently forecasting. Once the file is on the local system, MWFM extracts the required input parameters using WGRIB, which is a program designed for the management of GRIB data files. During this research, 12-hourly data were retrieved in GRIB format from the analysis through 48 hour forecast point. The AVN GRIB data files include information covering the globe at a 1° X 1° resolution, and they contain the necessary MWFM input parameters up to the 10 mb level.

3.2.3 MM5 Input Data. Since the MM5 was run at AFIT, the output data were available in a binary format native to the MM5. To facilitate using the data as input for the MWFM, MM5 data files were converted to GRIB format using the following procedure. The MM5 binary data file was first converted to the Grid Analysis and Display System (GRADS) format using the program GRADSV3, developed by George Bryan at PSU. GRADSV3 is a program designed to convert the MM5 binary data to a stream binary format that can be displayed by GRADS, an interactive product design for the visualization of scientific data. In order to save computation time and disk space, only the required MWFM input parameters over the desired geographical location were written to the GRADS file.

The MM5 GRADS data file were then read into GRADS and, using intrinsic GRADS functions, written to a single, new file in GRIB format. The GRIB file was created with a resolution of 0.5° X 0.5°, a time step of 12 hours, and contains the atmospheric parameters for all of the time steps. The large GRIB file was then parsed into separate files for each time step using the WGRIB utility, and the individual time

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step files were used by the MWFM. The accuracy of the file conversion process, from binary to GRIB, was evaluated subjectively by comparison. Graphical output created from the native MM5 binary data was compared side-by-side with graphical output from the GRIB data. In all test cases, the subjective evaluation indicated the data experienced little to no degradation during the conversion.

3.2.4 RAOB Input Data. The input data used during this research for the RAOB program were raw rawinsonde sounding data in text format. These data were obtained primarily from the University of Wyoming and Florida State University. For the purposes of comparison, ten stations in East Asia were chosen. Sounding data were collected for each forecast day at 00 and 12Z. The rawinsonde stations used for comparison are listed in Table 2, and their locations are shown in Figure 5.

Table 2. East Asia Rawinsonde Stations.

WMO Number	Station Name	Country	Latitude (N)	Longitude (E)
47122	Osan AB	ROK	37° 06'	127° 02'
47158	Kwangju AB	ROK	35° 07'	126° 49'
47138	Pohang	ROK	36° 02'	129° 23'
47580	Misawa AB	Japan	40° 41'	141° 23'
47681	Hamamatsu AB	Japan	34° 44'	137° 40'
47412	Sapporo	Japan	43° 03'	141° 20'
47600	Wajima	Japan	37° 23'	136° 54'
47646	Tateno	Japan	36° 03'	140° 08'
47778	Shionomisaki	Japan	33° 27'	135° 46'
47807	Fukuoka	Japan	33° 35'	130° 23'
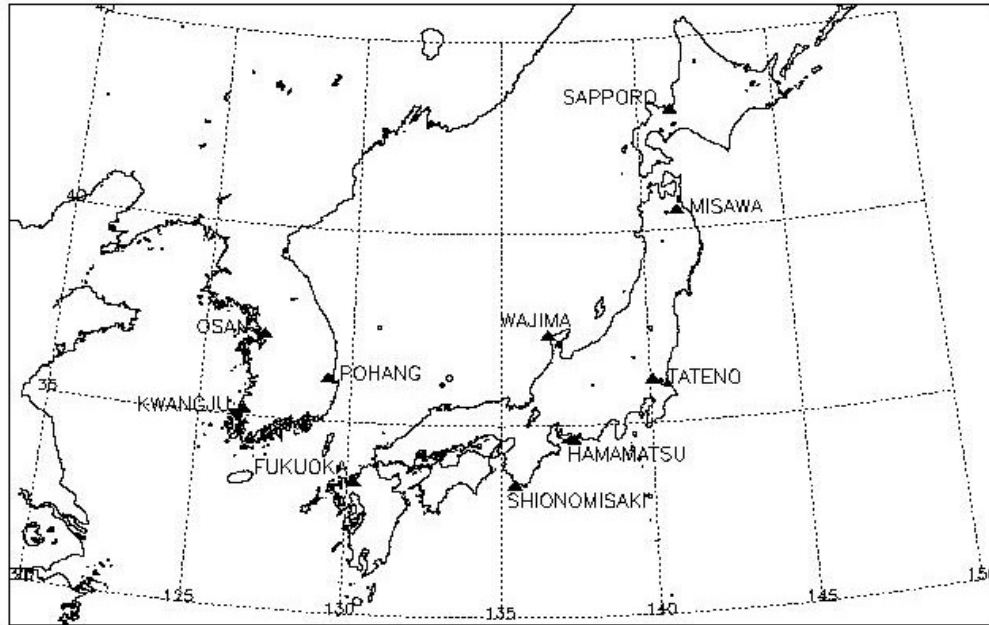
Figure 5. East Asia Rawinsonde Stations. Station locations are denoted by the ▲ symbol.

The raw sounding data includes the temperature, dew point temperature, pressure, and wind speed and direction for the atmospheric column. This column is assumed to be directly over the station that launches the balloon. However, this assumption is not entirely accurate since the atmospheric flow will typically carry the balloon downwind away from the station as it ascends. Errors in balloon location and height can occur if the balloon is not rising at the standard ascension rate of 300 meters per minute. Errors in sounding data can also occur due to the lag time of sensors in the instrumentation package. For example, if the balloon is passing through a rapidly changing layer, some of the information will not get reported since the instruments cannot react to the changes fast enough. The two main rawinsonde data concerns for RAOB are the temperature and pressure measurements. The typical lag for temperature sensors is 4 to 20 seconds, with

the lag increasing with altitude (Golden et al. 1986). The pressure measurements used for determining the height have a standard error of ± 1 mb at the surface and 10 mb with an error of ± 2 mb at 500 mb (Golden et al. 1986).

The raw data were retrieved for the above stations in the standard World Meteorological Organization (WMO) format. Data below 100 mb are described by two code groups, TTAA and TTBB. The TTAA grouping contains data at standard atmospheric pressure levels, and the TTBB group records significant data levels. The TTCC and TTDD groups contain standard pressure level information and significant level data above 100 mb, respectively. Complications during the flight of a balloon, such as equipment failure or premature popping of the balloon, may not allow for the collection of data for the entire atmospheric column. If the balloon does not ascend above 30 mb for a specific location, the location's sounding is disregarded and not used for forecast comparison during this research.

3.3 MWFM Configuration

3.3.1 General Information. The MWFM is designed in a modular configuration that allows the user to setup certain forecast guidelines that direct the model runs. For example, the user can choose the initialization hour, the first forecast hour, the MWFM version number, and the type of NWP data. If not input, the MWFM uses default values. The modules are a mixture of programs developed in both FORTRAN and Interactive Data Language (IDL), with the majority in IDL format. The MWFM was developed to

run in a UNIX/LINUX environment using csh/tcsh. The AFIT mountain wave forecasts are created on a Sun Solaris 8.0 computer in a SunOS/UNIX operating system under csh.

The top level of the MWFM is an IDL program that is used to setup the model based on user-supplied inputs. This level of the code is also used to control the number of forecasts performed. The user passes in values to "keywords" that the module uses to determine what type of NWP input data to retrieve, what version of the MWFM to run, the dates of forecasts to perform, and how to output the data. These input conditions are then passed down to sublevel routines. Successive levels of the program perform the necessary wave calculations, create the mountain wave plots, and perform file maintenance tasks.

Several modifications had to be made to the MWFM code to achieve the desired results of this research. The NRL designed the model to provide forecasts every 24 hours at 12Z. For operational use, the Air Force would require a forecast at least every 12 hours, specifically at 00 and 12Z. Therefore, the top level MWFM code was modified to include an option for 12 hourly forecasts, while retaining the initial NRL coding. This warranted the alteration of sublevel code that controls the incrementing of forecasts dates. The MWFM could easily be modified to provide more frequent forecasts as desired, assuming input data are available on the same temporal scale.

The MWFM was also modified to allow for the collection of momentum flux deposition values in text format. This change was implemented to allow an objective comparison of the MWFM output data versus a subjective comparison using the graphical output, shown in Figure 6. The peak momentum flux deposition value for each

longitude, latitude location at each of the desired levels was collected for further

investigation. Section 3.4 describes the comparison process in detail.
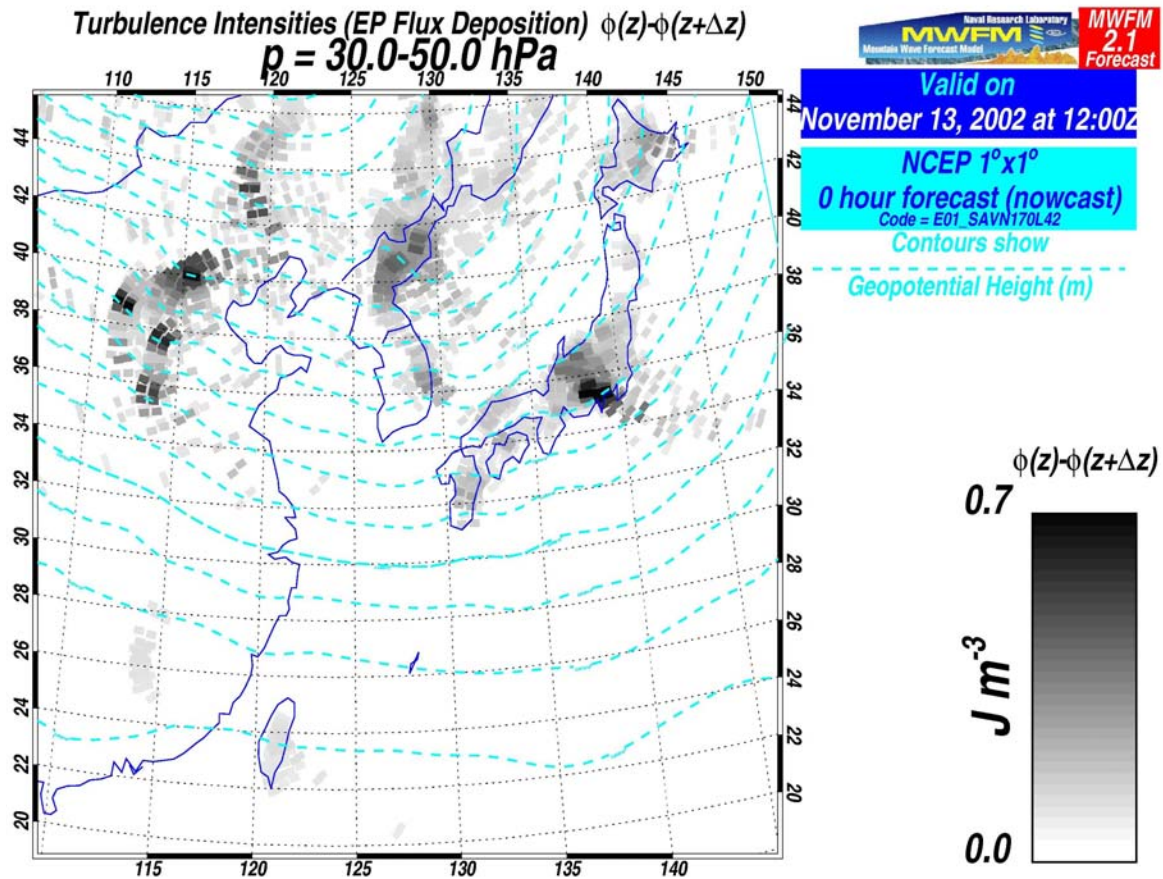
Figure 6. Graphical MWFM Forecast Output. An example of the graphical output for the 30-50 mb layer provided by the MWFM Version 2.1. The graphic shown is valid for 12Z November 13, 2002 and was created using 0 hour analysis AVN input data.

The MWFM runs jobs based on "special cases." The special cases are IDL

programs set up by the user containing information pertaining to the specifics of a

mountain wave forecast. To make a new special case, the user must create a "what2do"

file. Just as it sounds, the what2do code provides inputs to the MWFM explaining the

specific forecast requirements desired. Information provided by the what2do file

includes, but is not limited to, items such as: the latitude and longitude limits of the

forecast, the number and levels of mountain wave plots per timeframe, the number of ray

azimuths launched per ridge, the type of meteorological data to overlay on the plot, and

the name of output files. The specific structure of the what2do program used during this

research is described below.

3.3.2 AFIT What2do Configuration. The AFIT what2do case was setup to be used with

both the MWFM 1.1 and 2.1 versions. The exact program created for this research is

provided in Appendix A for review. The case was setup to default to MWFM version 1.1

forecasts using NCEP AVN data. The latitude and longitude limits were from 100° to

150° E longitude (negative values represent the western hemisphere) and 15° to 50° N

latitude. The design called for three mountain wave turbulence plots at the 70, 50, and 30

mb levels. Since turbulence is calculated by the difference in momentum flux from one

level to the next higher level if saturation is induced, the levels actually corresponded to

the layers 100-70 mb, 70-50 mb, and 50-30 mb. Turbulence displays were created using

a black-white scale IDL Colortable, and the output files were produced in postscript (.ps)

format. The code was also configured to perform a text data dump of the maximum

momentum flux deposition values.

For MWFM 2.1 forecasts, the number of ray azimuths to launch from each ridge

was set to 18. This corresponded to a maximum of 18 rays between 0 – 180° each

separated by 10° downwind from a ridge (Figures 1 and 2). The number of horizontal

wave numbers allowed for each ray was set at two. Therefore, for each ridge in the

forecast area, a total of 36 rays were launched.

3.4 Forecast-Observation Comparison Procedure

3.4.1 General Information. MWFM forecasts were accomplished twice daily extending

through 48 hours with a 12-hour time step using both the AVN and MM5 input data and

both MWFM versions. Forecast data were collected for 31 days. For the purposes of

comparison, rawinsonde data for the 10 selected locations (Table 2) were collected every

twelve hours for 33 days. The additional rawinsonde data were necessary for comparison

with the MWFM forecasts extending 48 hours after the final forecast day.

Data from each of the MWFM forecast time periods were amassed in both

graphical and text format. In order to present a more objective study, the text data were

the primary source of comparison data used during this research. Since turbulence

forecasts are the principal concern of this research, the maximum turbulent effect was

desirable, and this effect is assumed to be proportional to the value of momentum flux

deposition. Therefore, when collecting the MWFM data, the peak or maximum

deposition value for each longitude, latitude point at every requested level was collected.

If a rawinsonde sounding was missing for a particular time or the balloon did not reach

above 30 mb, the MWFM forecast was discarded.

The RAOB program was used to analyze each of the rawinsonde soundings for

the presence of Stratoturb. RAOB provided a graphical output of turbulence layers, an

example of which is provided in Figure 7. For this research, turbulence was considered

to be present in a layer if a graphical indication was located anywhere within the layer. The maximum intensity within each layer was also recorded for possible refinement of the turbulence intensity scale. Once again, it must be recognized that the RAOB analyses are not actual observations of turbulence, but merely diagnoses based on a conceptual model.
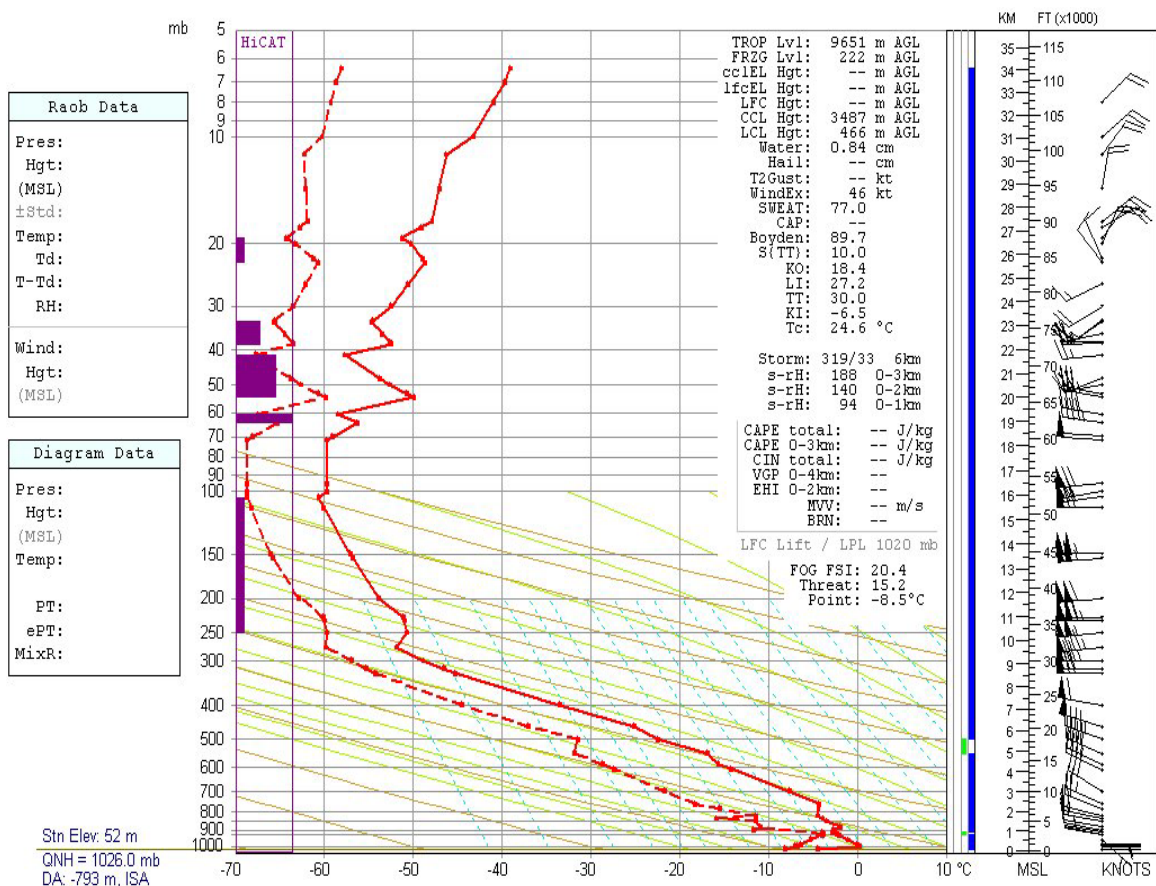
Figure 7. RAOB Graphical Turbulence Analysis. The dark colored bars on the left side of the diagram show the turbulence analysis. The extension of the bars towards the right indicates the intensity level of turbulence. From this image, the use of the 'S' layer model is evident (Section 2.5), with turbulence located in the mixing layer.

3.4.2 MWFM Forecast Comparison Against RAOB Analysis. As stated previously, the comparison between the MWFM forecasts and the RAOB analysis were performed using the text output from the MWFM and the graphical RAOB output. For each station's RAOB analyses throughout the time period, the presence of turbulence at each layer was recorded as either yes or no. For comparison, similar compilations of yes/no analyses were created for each station for every forecast time, MWFM version, and initialization model. A forecast was given a 'yes' assignment based on the presence of any value of momentum flux deposition within a 1.5°X1.5° data collection region (box) over each rawinsonde station. The collection area was positioned such that 90% of the area of the box was located downwind of the station. The downwind location of the box (Figure 8) was used in an effort to capture turbulence forecasts from the most likely environment of the actual rawinsonde observations. In a standard atmospheric setting, a balloon travels 1° to 1.5° downwind with the background wind flow, but may travel more or less. Therefore in an effort to collect the most representative turbulence data, the size of the collection box used during this research was a compromise.
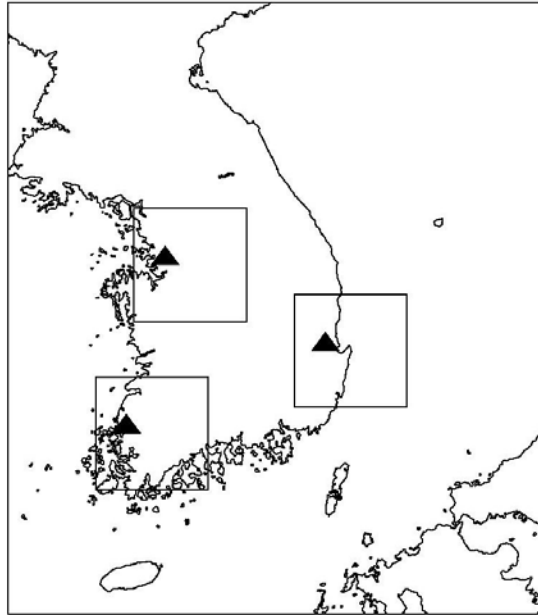
Figure 8. Downwind Turbulence Forecast Collection Area. Momentum flux deposition data was collected from all ten rawinsonde stations inside areas located primarily downwind from the station location. An example of the collection boxes over the ROK is pictured here.

3.5 Statistical Methodology

Contingency table analysis is used on populations that can be categorized into separate groups based on the characteristics or factors of the population members. The four factors describing the data were: forecast yes or no and observed yes or no. The data compiled from the comparisons of the MWFM forecasts and the RAOB analyses were divided into four separate categories, with each population member belonging only to one group. The four categorical groups of data were then described as combinations of the four possible factors. The four categories were: a) turbulence forecast and observed, b) turbulence forecast and not observed, c) turbulence not forecast but observed, and d)

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turbulence not forecast and not observed. Where, for the purposes of comparison during

this research, the RAOB analysis was considered an observation of turbulence. These

four categories were used to construct a two-way contingency table, shown in Figure 9-2.

Figure 9. Two-way Contingency Table. The two-way contingency table is used for
comparison of categorical data. Table 1 is an example of a table used for testing for
homogeneity. Table 2 is used for comparison of MWFM forecasts to RAOB analyses
(observations). Modified from Wilks (1995).

The contingency tables must be tested for statistical significance in order to derive

meaning from the results they present. The chi-squared (χ^2) test is typically used to test

for significance when all table cell counts are large. Basically, the chi-squared test

determines the dependence of factors used to categorize the data. Dependence of table

cell values on the contributing factors implies that the numbers were not generated by

mere chance, and the values have some meaningful interpretation. Tables determined to

be statistically insignificant show no dependence between the factors. The chi-squared

value for a two-way contingency table is calculated using Equation 7. For this research,

the p-value test was used with a critical value of 0.05 for significance.

$$\chi^2 = \sum_{AllCells} \frac{(ObservedValue - ExpectedValue)^2}{ExpectedValue} \qquad (7)$$

If the contingency tables are found to be statistically significant, the individual

cells of the tables are used to compute several measures of accuracy and skill, as shown

in Wilks (1995). The measures of accuracy computed were the hit rate, the false alarm

rate (FAR), the probability of detection (POD), and the critical success index (CSI). The

hit rate gives the percentage of the total number of forecasts resulting in a correct

forecast, either positive or negative. The FAR is the proportion of positive forecasts that

do not occur, while the POD is the percentage of events in which turbulence occurred and

was simultaneously forecast. CSI is an alternative to the hit rate measure where the

correct negative forecasts are removed. When used to compare the MWFM forecasts

with the RAOB analyses, these tests provide a measure of the agreement between the two

Stratoturb tools.

Wilks (1995) discusses various measures of forecast skill that are typically

calculated using contingency table analyses. One measure of skill is the Heidke Skill

Score (HSS). According to Wilks (1995), the HSS compares the results in the

contingency table to a reference, random forecast, with the constraint that the random

forecast table has the same marginal probabilities as the actual forecast table. The hit rate

of the reference forecast is compared to the hit rate of the table. A HSS of 0 indicates the

forecasts are equivalent to the reference forecast, while a score of 1 is a perfect forecast.

A negative HSS shows that the forecast has no skill over the random, reference forecast.

Since a comparison was being made using the RAOB analyses and these analyses

were not true measurements of turbulence, the HSS may have been biased because the

random table and the forecast table must have the same marginal probabilities. If the RAOB analyses' marginal probabilities were skewed towards high values of either yes or no, for example 80% yes and 20% no, the MWFM forecasts were not likely to show significant skill by comparison. Similar biases are seen for the other skill statistics presented by Wilks (1995). For this reason, the results of the skill statistics were not reliable as a measure of forecast skill since RAOB is not truth. Therefore, the skill scores were not used as a means of comparison between the MWFM and RAOB.

The contingency tables were also used to test for bias between the two populations used to create the table. For example, the bias was calculated to determine if MWFM was forecasting more occurrences of turbulence than RAOB was analyzing. Bias was evaluated by comparing the number of yes forecasts to the number of yes analyses. A bias of one indicates that the MWFM was forecasting turbulence the same amount as RAOB is analyzing its presence. Bias greater than one denoted overforecasting, and bias less than one represented underforecasting (Wilks 1995). It is important to note that bias is not a measure of accuracy or skill, as it does not take into account if the forecast and analysis occurred at the same time.

Beyond tests of accuracy and skill, the contingency table was also used to test for homogeneity, as described by Conover (1971). Basically, data from two populations given the same treatment are categorized based on output qualities, in this case whether turbulence was forecast or not. For example, the forecasts created using the two different MWFM versions comprised two populations. Therefore, contingency table analysis for homogeneity was used to determine if differences existed between using one version versus the other.

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Examining Figure 9-1, the table was set up such that the column labels were no longer observed yes or no, but they were now MWFM 1.1 (Version 1.1) or MWFM 2.1 (Version 2.1). Assuming there was no difference between the versions, the test for homogeneity implied that the probability of getting an observation in cell 'a' is equal to the probability of getting an observation in cell 'c,' likewise for 'b' and 'd'. Once again, the chi-squared test was used to determine the significance of the table. Significance implied that homogeneity did not exist for the cells of the contingency table.

IV. Results

4.1 Introduction

      This chapter presents a summary of the contingency table statistical analyses completed during this research. The analyses detail differences found between forecasts created using the two MWFM versions, the two NWP sources, and their combinations. A comparison of the MWFM forecasts to the RAOB HiCAT turbulence analyses is also presented.

      The MWFM data collected were split between several factors: the version of the MWFM used, the source of the input data, the layer of the atmosphere, and the forecast hour. As a result, there were several comparisons that needed to be analyzed. First, it was necessary to determine if one MWFM version produced different forecasts than the other and whether or not one compared better to the RAOB analyses. A second question that needed to be answered was the effectiveness of the input data. Will one source be preferable to the other, or did they produce conflicting forecasts of turbulence? Lastly, it was important to know how the MWFM forecasts varied from one atmospheric layer to another. Included in all of these comparisons was the effectiveness of the MWFM as the forecast hour increased. It is crucial to note that these factors are likely to be intertwined with one another. The above concerns were addressed as follows.

4.2 Comparison of MWFM Versions

It is important to understand the difference between the two versions of the MWFM. Neither of the two versions is extremely computationally expensive, but the MWFM 2.1 does require more processing time due to the increased number of mountain waves it must initiate and track for each ridge. If the two versions are producing similar forecasts of turbulence, it may be beneficial to implement the simpler MWFM 1.1 to save computation time. Therefore, a comparison of the two versions is valuable when assessing which version is most efficient for an operational setting.

Initially, the data from each of the rawinsonde stations, atmospheric layers, and input sources were combined into summary datasets. The combination provided datasets divided only by the MWFM version and the forecast hour, and it was useful in developing a large-scale picture of the version differences. First, the datasets were analyzed for homogeneity employing contingency tables using the chi-squared test for significance. All of the five contingency tables created from the above dataset indicated a statistically significant difference between the forecasts created by the different versions, or non-homogeneity. If the data were separated further into datasets divided by atmospheric layers, 15 tables were created. All of the tables showed non-homogeneity between the versions. The datasets were divided again based on which input source was used. Of the 30 tables generated, 86.7% of the tables were non-homogeneous. Therefore, it can be stated with high confidence that the two MWFM versions generated statistically different turbulence forecasts regardless of the atmospheric layer or the input

data source. Hence, more study into the accuracy of the different versions must be completed to determine the superiority of one version over the other.

The summary dataset used initially for the homogeneity tests was used for comparison of the MWFM forecasts against the RAOB analyses. Accordingly, the contingency table analysis was employed in an effort to determine measures of accuracy. The data resulted in ten contingency tables, one for each version at each forecast time. All of the tables were found to be significant, the implications of which were described previously. Tables 3 and 4 show the results of the various accuracy measures for the initial forecast time through 48 hours for each MWFM version compared to RAOB.

Table 3. MWFM Version 1.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	47.61	36.64	19.85	40.30	0.50
12 Hour	47.75	36.74	20.64	40.62	0.51
24 Hour	47.99	37.13	21.09	41.22	0.52
36 Hour	47.21	36.54	21.64	40.64	0.52
48 Hour	47.74	37.42	21.17	41.60	0.53
Average	47.66	36.89	20.88	40.88	0.52

Table 4. MWFM Version 2.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	57.38	51.75	22.33	60.80	0.78
12 Hour	55.09	48.68	23.10	57.01	0.74
24 Hour	55.38	49.22	23.59	58.04	0.76
36 Hour	54.79	48.85	23.96	57.74	0.76
48 Hour	56.52	50.62	22.48	59.32	0.77
Average	55.83	49.82	23.09	58.58	0.76

Version 2.1 forecasts showed a slim advantage compared to Version 1.1, although neither had particularly outstanding numbers. Comparison of the results from the above tables indicated that throughout the 48 hour forecast period, Version 2.1 had the higher

hit rate and CSI, with averages of 55.83% and 49.82% respectively. The POD for

Version 2.1 was also better, and the Version 1.1 FAR was slightly lower. The bias scores

indicate that each of the versions was underforecasting compared to the RAOB analyses,

with the Version 1.1 indicating Stratoturb approximately half as much as RAOB.

It is interesting to note that the results shown for the two versions did not vary

greatly as forecast time increases. Typically, forecast accuracy and skill are expected to

decrease as forecasts depart farther from the initialization time. The lack of decrease in

skill appeared to be another indicator of the poor comparison of the MWFM forecasts

with the RAOB analyses.

4.3 Comparison of MWFM Input Data Sources

When used operationally by AFWA, the initialization data provided to the

MWFM must come from a reliable and accessible source. The two sources of data used

during this research are currently readily available at AFWA on a daily basis. However,

there are pros and cons for picking one source of data versus the other. The AVN data is

global, but it comes from an outside location and may not be reliably available for use.

The MM5 data is internally produced and can be changed to provide both the temporal

and special resolution required for operational use. Also, for AWFA to implement the

MWFM using MM5 data, they would have to reconfigure the pressure top of their model

to encompass the desired forecast levels. This would take time and computing resources,

but AFWA is capable of making the changes if desired.

To facilitate analysis, the data were compiled into a large, summary dataset combining the rawinsonde stations, the atmospheric layers, and the MWFM versions. The dataset was divided only by forecast time and input data source. The contingency table analysis showed significant statistical difference (non-homogeneity) in all of the 5 tables created. Therefore, the dataset was separated based on atmospheric layer for further analysis. Of the 15 tables generated, 93.3% were non-homogeneous indicating that the atmospheric layers were not an important factor in the overall difference between forecasts generated using the two NWP input data sources.

To provide further insight into where the differences between the NWP input sources originates, the dataset was divided based on the MWFM versions, creating 30 contingency tables. Overall, 43.3% of the tables were statistically homogeneous. All of the homogeneous tables were generated from data within the Version 1.1 split, so that 86.7% of the Version 1.1 split was homogeneous. Therefore, the tables within the Version 2.1 split were all non-homogeneous. Based on these results, there was no statistical difference between the MWFM 1.1 forecasts using the AVN and MM5, and there was a statistical difference in MWFM 2.1 turbulence forecasts. The difference between the forecasts suggested the MWFM was receiving different input from the two NWP models, and that Version 2.1 was more sensitive to variations in the input parameters than Version 1.1.

The combined summary dataset was also used to test for accuracy differences between forecasts created using the two input sources and RAOB analyses. There were ten contingency tables analyzed during the source data comparisons, all of which were statistically significant with a p-value less than 0.05. The performance of the MWFM

with respect to the initialization data source is shown below in Tables 5 and 6. As with

the MWFM version comparison, the results did not indicate a good agreement between

the MWFM forecasts and the RAOB analyses. The tables show that the AVN had a

slight advantage in all of the measures of accuracy, excluding FAR. The apparent

underforecasting of the MWFM compared to RAOB was again evident in the bias scores.

Table 5. MM5 Initialization Data Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	50.86	41.93	21.01	47.19	0.60
12 Hour	48.26	38.01	21.61	42.46	0.54
24 Hour	48.97	39.18	22.23	44.12	0.57
36 Hour	48.55	38.94	22.42	43.88	0.57
48 Hour	49.00	39.51	21.61	44.33	0.57
Average	49.13	39.51	21.78	44.40	0.57

Table 6. AVN Initialization Data Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	54.14	46.91	21.67	53.91	0.69
12 Hour	54.57	47.57	22.46	55.18	0.71
24 Hour	54.41	47.40	22.84	55.14	0.71
36 Hour	53.45	46.69	23.49	54.50	0.71
48 Hour	55.25	48.72	22.21	56.59	0.73
Average	54.36	47.46	22.54	55.06	0.71

4.4 Comparison of Source-Version Combinations

Initially, each of the four permutations of NWP source and MWFM version were

tested for homogeneity with the RAOB turbulence analyses. Twenty contingency tables

were created for these tests, all of which were found to be statistically significant and

therefore displayed no homogeneity. The contingency tables results showed that the

MWFM Stratoturb forecasts and the RAOB analyses are significantly different.

The next step was to compare the accuracy measures for the various combinations of the input data sources and MWFM versions. Due to the inherent differences in the way the AVN and MM5 model the atmosphere, this analysis was accomplished to determine if one version of the MWFM worked more efficiently with one type of input data when compared to the RAOB turbulence analyses. For this procedure, 20 contingency tables were created. Three of the 20 tables (15%) had p-values greater than 0.05 and were therefore be considered statistically insignificant, although, only one table (5%) would have fallen outside a p-value of 0.1. The results of the accuracy and skill measures for the input source-version combinations are shown in Tables 7 through 10.

Table 7. MM5-Version 1.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	47.86	37.01	19.87	40.75	0.51
12 Hour	46.44	34.84	20.74	38.34	0.48
24 Hour	47.32	35.95	20.72	39.67	0.50
36 Hour	47.15	36.21	21.18	40.11	0.51
48 Hour	47.46	36.82	20.78	40.76	0.51
Average	47.25	36.17	20.66	39.93	0.50

Table 8. MM5-Version 2.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	53.86	46.63	21.85	53.63	0.69
12 Hour	50.09	41.08	22.31	46.57	0.60
24 Hour	50.61	42.29	23.42	48.57	0.63
36 Hour	49.94	41.58	23.44	47.65	0.62
48 Hour	50.54	42.12	22.29	47.91	0.62
Average	51.01	42.74	22.66	48.87	0.63

Table 9. AVN-Version 1.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	47.37	36.28	19.84	39.85	0.50
12 Hour	49.06	38.62	20.54	42.90	0.54
24 Hour	48.66	38.30	21.44	42.78	0.54
36 Hour	47.27	36.87	22.09	41.17	0.53
48 Hour	48.01	38.01	21.55	42.44	0.54
Average	48.07	37.62	21.09	41.83	0.53

Table 10. AVN-Version 2.1 Accuracy and Bias Results.

	Hit Rate	CSI	FAR	POD	Bias
00 Hour	60.91	56.66	22.71	67.97	0.88
12 Hour	60.09	55.80	23.64	67.46	0.88
24 Hour	60.16	55.80	23.71	67.51	0.88
36 Hour	59.64	55.69	24.32	67.83	0.90
48 Hour	62.50	58.63	22.60	70.74	0.91
Average	60.66	56.52	23.40	68.30	0.89

Results from the previous two sections showed that the MWFM Version 2.1 had higher test percentages than Version 1.1, and the AVN initialization data had slightly higher numbers as well. The tables above reveal that the combination of Version 2.1 and AVN showed the most agreement with RAOB. Any combination of source data and Version 2.1 was closer to RAOB than Version 1.1. The AVN-Version 1.1 and MM5-Version 1.1 groupings were basically statistically equivalent. Bias scores showed an increase in agreement between the MWFM and RAOB when using Version 2.1, but the scores still indicated a tendency of the RAOB product to overanalyze the presence of Stratoturb when compared to MWFM. Ultimately, the comparison of the MWFM forecasts and RAOB analyses showed no strong agreement.

4.5 Atmospheric Layer Comparisons

The previous results were tabulated for the different MWFM versions and initialization sources using datasets where the atmospheric layers were combined. The next step was to calculate the accuracy measures using datasets separated with respect to the three layers. The new datasets were also split based on the version and input data source. These sets resulted in 60 contingency tables. Examination of the tables showed that only 22 of the 60 tables (36.7%) were statistically significant. Therefore, the common accuracy measures used previously could not be applied to a majority of the tables. Instead of dealing only with the significant tables, the information in the tables was inspected for some practical significance, as an alternative to statistical significance. Practical or managerial significance may allow important trends in the data to be recognized and used to make operational decisions. The statistical significance of certain tables will be mentioned when relevant.

After close examination of the atmospheric layers data, a trend was recognized. For each source-version combination, the number of positive MWFM forecasts, given turbulence was analyzed by RAOB, increased as height in the atmosphere increased. This trend was evident in the bias scores calculated for each layer, shown in Figure 10. The figure shows that for each NWP source-MWFM version combination, the bias increased towards one as height in the atmosphere increases. The significant tables for the 50-30 mb layer using both MM5 and AVN combined with Version 2.1 showed hit rates between 65-75%, with the AVN hit rates higher than the MM5. FAR in this layer are less than 18%.

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As expected from the results of the combined layer tests, the Version 2.1 figures

displayed more agreement with RAOB than those of Version 1.1 for all layers. Both of

the version's agreement appeared to increase from the 100-70 mb layer to the 50-30 mb

layer. The 100-70 mb layer had the least amount of difference between the two versions,

while the 50-30 mb layer had the greatest. This trend agreed with the improvement of the

MWFM and RAOB agreement as height in the atmosphere increases.
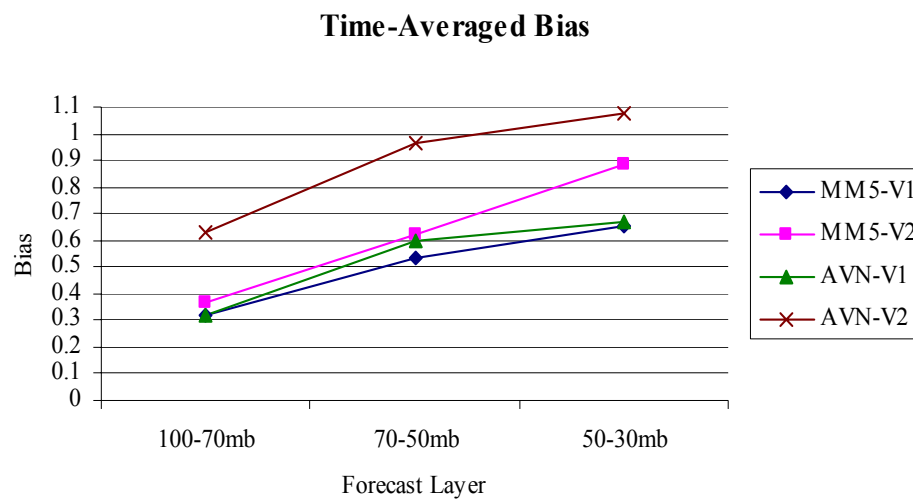
Time-Averaged Bias

Figure 10. Time-Averaged Bias with Height of the NWP Source-MWFM Version
Combinations.

4.6 Refinement of the MWFM Turbulence Intensity Scale

Once it became apparent that in situ observations of Stratoturb were unavailable

and the change to comparison with RAOB analyses was made, the goal of refining the

turbulence intensity scale created by the NRL was not actively pursued. Since the RAOB

analyses were not true measures of turbulence, it was decided that any changes to the

intensity scale, which was subjectively developed based on NASA ER-2 missions, would

be detrimental and inappropriate.

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V. Conclusions and Recommendations

5.1 Conclusions

The primary purpose of this research was to provide AFWA with a means of predicting stratospheric turbulence using NWP data they already have on hand. This goal has been accomplished through the acquisition of the MWFM from the NRL. The gravity wave model can provide AFWA with turbulence forecasts for any geographical location at the desired atmospheric levels of 30, 50, and 70 mb. The MWFM was designed to provide graphical output and, with slight modification, can provide a text output in any desired format.

Secondary goals of this research were to successfully verify the MWFM in order to prove its forecasting accuracy and to improve the current turbulence intensity scale developed by the NRL. These secondary objectives were not fulfilled. Ultimately, the reason for both failures was the lack of an appropriate verification data source. The best method of verification for this type of product would be direct measurement or sensing of turbulence by aircraft flying at stratospheric altitudes. Although efforts were made to acquire such data, the necessity to keep certain aspects of military operations secure mired the process. As a result, an alternate means of substantiation had to be found.

As an alternative to direct verification of the turbulence forecasts, the RAOB program's HiCAT analysis was used as a means of comparison. This product was chosen since it is currently used as the "first option" by operational weather units in the geographical focus region to warn aircrews of Stratoturb hazards (McQuoid 2002). Since

RAOB's turbulence analyses are not direct measurements of turbulence, the data could not be used for verification of the MWFM forecasts. Therefore, the two turbulence products could only be evaluated to determine how they compare to one another.

The fact that the RAOB analyses are not actual measurements of Stratoturb cannot be overstated. Accordingly, the accuracy scores calculated from the MWFM versus RAOB contingency tables do not objectively describe the accuracy of the MWFM in regards to forecasting Stratoturb. Instead, the objective comparison of the MWFM forecasts to the RAOB HiCAT analyses was used to formulate a subjective assessment of the MWFM's value to the Air Force.

The subjective conclusions drawn about the MWFM when compared to RAOB are possible based on descriptions of the RAOB analyses' effectiveness provided in correspondence with Major Taylor (2002), the Assistant Director of Operations (ADO) for the 5th Reconnaissance Squadron (5RS) stationed at Osan AB, ROK. The 5RS receives the RAOB HiCAT product daily in support of U-2 operations. The overall impression of the RAOB product from pilots in the 5RS is that it routinely overanalyzes the presence and intensity of Stratoturb, and they also expressed displeasure with the lack of geographical coverage provided by the RAOB product. According to Major Taylor (2002), "there is no geographic location information associated with the turbulence forecast and that type of information is specifically what we need."

The propensity of the RAOB HiCAT analyses to overestimate the presence of turbulence was illustrated by the results of the bias tests performed during the comparison of MWFM to RAOB and by examination of the marginal probabilities of RAOB analyses. The bias scores indicated overall that RAOB was analyzing the presence of

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turbulence more often than the MWFM, as much as two to one. The marginals showed

that positive RAOB analyses of turbulence typically exceed negative analyses three to

one. These results did not seem realistic and provided further evidence of RAOB's

overanalysis. Although it cannot be objectively verified which product is more accurate,

based on the practical knowledge provided by the 5RS, the skewed marginal

probabilities, and fact that the MWFM is a physically based model, it is likely that the

MWFM forecasts of turbulence provide a more accurate assessment of the presence of

Stratoturb.

Personal correspondence with Dr. Eckermann (2002) from the NRL revealed that

the NASA ER-2 flight crews have great confidence in the MWFM turbulence forecasts.

Based on their past experience with the MWFM, the ER-2 flights will avoid areas where

turbulence is predicted. Due to the lack of flights into possible turbulent regions,

verification of the MWFM turbulence forecasts by the NRL would be limited primarily to

confirmation of negative turbulence conditions.

The MWFM is clearly a better product when considering spatial and temporal

coverage of Stratoturb forecasts. The MWFM has the ability to display a graphical image

over any location and for any atmospheric layer available in the NWP input data. Also,

the MWFM can create forecasts for any forecast time at which NWP data is available, as

opposed to a hindcast provided by the RAOB program. When the above conclusion

concerning the RAOB program's bias is combined with the graphical display and forecast

capabilities of the MWFM, the MWFM program is the best choice for use by the Air

Force as a Stratoturb prediction tool.

The statistical analyses highlight the differences between forecasts created using the MWFM versions. It is clear that the two versions are producing different forecasts, but it cannot be determined which is the most accurate. Based on the method used by each of the versions to model wave propagation, Version 2.1, which has the capability of forecasting both vertically propagating and trapped mountain waves, is likely to be the most effective. Although, a more objective study of the two versions is required to clearly state which is more accurate.

Both of the NWP input data sources produced similar results when used to provide atmospheric parameters to the MWFM. The forecasts generated using Version 1.1 in combination with both NWP sources were not statistically different. Statistical differences in the forecasts created using Version 2.1 with the two NWP sources were seen. These problems may be attributed more to set up of the MM5 forecast window than any model deficiency. For the duration of this research, the MM5 forecast window was not optimally placed since the western edge of the window was located over the Tibetan Plateau (Figure 3). The terrain feature on the window edge may have caused errors in the boundary conditions to be translated through the remainder of the window during the forecast period. This problem is easily fixed by expanding the window upstream to encompass the entire Tibetan Plateau. AFWA is currently running MM5 windows with 45 km resolution that are located to mitigate terrain induced boundary errors. Both NWP sources can therefore be used with the MWFM.

5.2 Recommendations

5.2.1 Recommendations to AFWA. The MWFM can provide the Stratoturb forecasts at

the needed levels for AFWA. Since the MWFM is freely available to the Air Force, it is

recommended that AFWA implement it as soon as possible. The MWFM appears to

alleviate the overanalysis problem that is reportedly inherent in the current operational

product. The MWFM gives the customer the benefit of a graphical display of turbulent

regions over a wide geographical area versus a product valid only for a specific point

location. The MWFM can be configured to provide forecasts for specific contingency

locations or used over an entire theater of operations. The MWFM also provides the user

the capability to produce forecasts versus one-time hindcasts of turbulent conditions.

Once in place, the MWFM can be further scrutinized to verify its accuracy using actual

turbulence observations.

AFWA has the AVN data already in place for use in daily operations. It would

not be difficult to use this data for the initialization of the MWFM. If AFWA decides to

raise the pressure top of the MM5 or implement an increased pressure top with the

Weather Research and Forecast (WRF) model, the data can easily be used with the

MWFM with minor code modifications. The NRL is providing both versions of the

MWFM, and since neither version is computationally expensive, it may be possible to

run both versions simultaneously and provide both forecasts to the operational forecast

units.

5.2.2 Future Research Recommendations. There are many alternative research approaches that could be taken with future MWFM studies. The first and most important should be a study using actual turbulence observations from aircraft at stratospheric altitudes. For completeness, it would be interesting to study the accuracy of the RAOB program analyses in conjunction with the MWFM. Using the in situ aircraft measurements of turbulence, it would be possible to determine if the RAOB is effectively diagnosing the presence of Stratoturb. This is important because of RAOB's daily use in Air Force operations, and would provide an objective comparison of the two Stratoturb tools.

Although the turbulence forecasts for this research were made by analysis of momentum flux deposition, the MWFM can also model peak wave amplitudes and vertical velocities in the atmosphere due to gravity waves. A vertical velocity study may be an alternative to the flux deposition turbulence forecasts. The Global Hawk UAV makes routine measurements of vertical velocities while in flight, and these data may be used as verification for MWFM vertical velocity forecasts.

Future research with the MWFM should involve studies into the effects of increased vertical resolution of the NWP source data, due to the layered nature of the momentum flux deposition forecasts. Once saturation is invoked, turbulence is calculated based on the reduction of momentum flux to the value of the saturation limit. The resolution of the vertical layers of the input data from the NWP models may be spread too far apart to diagnose turbulent conditions between the levels. In the standard atmosphere, there is approximately a 2 km spread between the 100 to 70 mb and 70 to 50

mb levels, with nearly 3 km between 50 and 30 mb. Turbulent conditions can easily exist in such large layers of the atmosphere.

Finally, the NRL is currently working on an improved version of the MWFM. The MWFM 3.0 is being tested and may be available to the Air Force for future use. Open communications should be maintained with the scientists at the NRL in order to facilitate acquiring this model once it becomes available.

Appendix A: AFIT what2do Program

This is the IDL code used to create the what2do program called during this
research. This version of the what2do was created from a template provided by the NRL.
This version has been commented extensively and also contains a large amount of error
checking code. The comment lines in IDL are denoted by a semicolon (;) at the
beginning of the line or sometimes on the same line as code to provide information about
the statement. Line continuations are marked by the dollar sign ($). The "what"
structure that is created at the end of the code is return to the main MWFM program to be
used throughout the remainder of run. This "what" structure contains the information
necessary for the MWFM to produce the mountain wave forecasts desired by the user.

```
PRO WHAT2DO_AFITASIA,date=date,pole=pole,xrang=xrang          $
         ,field=field,levels=levels,latlonlims=latlonlims          $
         ,what=what,source=source,grid=grid                        $
           ,sequence=sequence,special=special                      $
           ,psfile=psfile,mwfmversion=mwfmversion                  $
           ,srcplane=srcplane,strict18=strict18,map_ann=map_ann    $
           ,plot_items=plot_items
;+
;                 =========================
;                 |     (       )      (        |
;                 |  M   )  W  (   F   )   M   |
;                 |     (       )        (        |
;                 |_____/^\_____/^\_____/^\_____ |
;                 | Mountain Wave  Forecast Model |
;                 ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
;
; -------------------
; WHAT2DO_AFITASIA
; -------------------
; template what2do_xxxx.pro routine to set up a new MWFM experiment: replace
;   "xxxx" with your experiment name and change various what.* values below to
;   tune to your specific experiment, then set up your own drv_xxxx.pro (MWFM 1.*)
;specialcase in special_cases.pro (MWFM 2.*).
```

```
;
; ------------------
; MWFM USAGE         e.g., special_cases.pro (source/jobs/what2do)
;      LOCATION       source/jobs/what2do
; ------------------
; HISTORY
; 20020811 SDE: created as a standardized what2do template from cleaned,
;               commented, and documented what2do_usarayforecast.pro
; ------------------
; KEYWORDS/PARAMETERS
;
;  date         input of standard character date in YYMMDD or YYMMDDZZ
;               format: gets plugged into what.date. You should always
;               pass a date, otherwise you'll get an unsatsifactory
;               default
;  pole         2-element vector of the "map pole" or center of the map,
;               in the format [longitude,latitude]. If not input, uses a
;               default value set below: gets plugged into what.pole
;  xrang        2-element x range vector for GSFC map sizing, used
;               explicitly only for map_source=0. For new IDL maps it
;               is only used unless the (much preferred) explicit sizing
;               option "platlonlims" in the pltrec structure (i.e.,
;               pltrec.platlonlims) is not set. If not input, uses a
;               default value set below: gets plugged into what.xrang
;  field        multi-element vector (# elements corresponding to the
;               number of requested forecast plots), containing integer
;               MWFM wave field indicies corresponding to various MWFM
;               output fields that can be calculated. Type
;               FIELD_STRINGS, /LIST within MWFM to see currently
;               supported list of permitted wave field indices and what
;               they correspond to. If not input, field is set to
;               default values set below: field gets plugged into
;               what.field
;  levels        a multi-element vector of exactly the same size as field
;               that represents the integer index values of the pressure
;               at which you wish to do this forecast. This is dependent
;               on the pressure level array of your particular atmospheric
;               data source: MWFM has pressures that go from largest
;               (low altitude) to smallest (highest altitude), so that if
;               the pressure level array is [1000.0,925.0,850.0,700.0....]
;               then level=[0,1,3] tells MWFM to plot 3 forecasts: first
;               on the 1000hPa surface, second on the 925hPa surface and
;               the third on the 700hPa surface. The field plotted in
;               each case is given by the field array above: e.g.,
;               field=[0,0,0] will plot peak vertical displacements in
;               each case. To find out allowable pressure surfaces, you
```

```
;                will need to read your data in using get_glbdata.pro and
;                then print out the returned plev array. If not input,
;                levels is set to default values set below: levels gets
;                plugged into what.levels
;   latlonlims     a 4-element array that defines the regional
;                longitude-latitude bounds [lonmin,lonmax,latmin,latmax]
;                within which MWFM will do the forecast. For example,
;                latlonlims=[-10.0,30.0,60.0,70.0] performs a forecast
;                in the longitude range 10W to 30E and for latitudes
;                between 60N and 70N, which corresponds roughly to
;                Scandinavia. See get_glbdata.pro for more
;                information/context. If not input, latlonlims is set to
;                default values set below: latlonlims gets plugged into
;                what.latlonlims
;   what          the output "what2do" structure that this routine returns,
;                containing all the information and swtiches needed to
;                run this particular MWFM forecast/analysis run just the
;                way the user wants. See the structure assignment
;                statement below for all the information within it and
;                what it all means, or else type HELP, what, /STRUCTURES
;                after calling this routine using what=what
;   source       specify the source string: type GET_GLBDATA,/LIST to get
;                listing of currently supported atmospheric data sources.
;                e.g., source='NMC' specifies NCEP/NMC data. If not input,
;                source is set to default values set below: source gets
;                plugged into what.source
;   grid         the grid string in GSFC format: e.g., 'GG2%5X2%5' for 2.5x
;                2.5 degree lon-lat gridding in the file. Gets plugged into
;                what.grid
;   sequence    the sequence data string in GSFC format, e.g., 'E01'
;   special     the special data string in GSFC format, again identifying
;                the specfic kind of atmospheric data file we're reading
;   psfile       if set true, activates postscript output via what.psfile=1
;   mwfmversion    passes the MWFM version (1, 2, ....)
;   srcplane    string used to signify the source of aircraft data to be
;                overplotted (e.g., 'ER2')
;   strict18     older keyword in which atmospheric data at 18 standard
;                pressure levels is strictly enforced. If press=-1
;                then it requires data at all X levels (I think)
;   map_ann    older map annotation keyword
;   plot_items  another plot annotation device, this time a structure
;                used to annote something to a plot. For a sample, see
;                code in what2do_solve.pro
;***************************************
;
;AUTHORIZATION TO USE AND DISTRIBUTE
;***************************************
;
```

```
;********************************************************************
;
;
PRINT, '*************************************************'
PRINT, '**************** what2do_afitasia ******************'
PRINT, '*************************************************'
PRINT, '*************************************************'

IF (NOT KEYWORD_SET(mwfmversion)) THEN mwfmversion=1   ;default to old
MWFM 1.*
;
; we must have a date
;
IF (NOT KEYWORD_SET(date)) THEN BEGIN
  date='00012300'
  DATE2STRING, date, sdate=sdate, /cen, hour=hour
  MESSAGE, '        *********WARNING*********        ',/INFORMATIONAL
  MESSAGE, 'Date string not input as keyword date=date', /INFORMATIONAL
  MESSAGE, 'Choosing default of '+sdate+', '+hour+'Z', /INFORMATIONAL
  MESSAGE, '       *********END WARNING*********
',/INFORMATIONAL
ENDIF
;
; set the atmospheric data source as defined in the GSFC-like method by 4
;   character strings: source=major source of the data, sequence=basic type
;   of forecast/analysis from this source, special is a special identifier
```

```
;    associated with sequence variations, and grid is the latitude-longitude
;    resolution of the atmospheric gridding (e.g., grid='GG2%5X2' means 2.5
;    degrees longitude by 2 degrees latitude)
;
IF (NOT KEYWORD_SET(source)) THEN source='NMC' ELSE $
   source=STRCOMPRESS(STRUPCASE(source),/REMOVE_ALL)
IF (NOT KEYWORD_SET(grid)) THEN grid='GG1X1'
IF (NOT KEYWORD_SET(sequence)) THEN sequence='pre'
IF (NOT KEYWORD_SET(special)) THEN special=''
;
; check/set up field and level arrays for all the necessary plots
;    see FIELD_STRINGS, /LIST for permitted fields and their field code
;    see plevs from get_glbdata.pro for range of permitted level indices
;
IF NOT KEYWORD_SET(field) THEN BEGIN
   CASE source OF
    'ASM':  field=[0,2,0,2,0,2]
    ELSE:   field=[2,2,2]           ; Output 3 turbulence charts
   ENDCASE
ENDIF

; set pressure levels to output
;             20=70mb
;             21=50mb 22=30mb 23=20mb 24=10mb
;
IF NOT KEYWORD_SET(levels) THEN BEGIN
   CASE source OF
    'ASM': levels=[10,10,16,16,19,19]
    ELSE:  levels=[20,21,22]           ; Output levels 70, 50, 30mb
   ENDCASE                             ; array same length as field
ENDIF
;
; check field and level array lengths, then set number of plots (nplots)
;
IF (N_ELEMENTS(field) NE N_ELEMENTS(levels)) THEN BEGIN
   MESSAGE, '       *********WARNING*********       ',/INFORMATIONAL
   MESSAGE, 'field & levels do not have the same # elements', $
      /INFORMATIONAL
   MESSAGE, $
      'longer array will be truncated to make sizes the same', $
      /INFORMATIONAL
   MESSAGE, '       *********END WARNING*********
',/INFORMATIONAL
   nplots=MIN([N_ELEMENTS(field),N_ELEMENTS(levels)])
ENDIF ELSE $
   nplots=N_ELEMENTS(field)
```

```
MESSAGE, STRTRIM(STRING(nplots),2)+' MWFM Plots have been requested', $
   /INFORMATIONAL

IF NOT KEYWORD_SET(latlonlims) THEN BEGIN
   latlonlims=[100.,150.,15.,50.]          ;set for east Asia theater
ENDIF ELSE $

   IF N_ELEMENTS(latlonlims NE 4) THEN BEGIN
     PRINT, 'latlonlims = ',latlonlims
     MESSAGE, ' latlonlims must be a 4-element vector'
     RETURN
   ENDIF
;
; set map sizes and center/"pole" location
;
IF NOT KEYWORD_SET(xrang) THEN BEGIN   ;pltrec.platlonlims can also be
used
   xrang=[-0.425,0.425]          ;set your own preferred default xrang here
   xrang=[-0.25,0.25]
ENDIF

IF NOT KEYWORD_SET(pole) THEN BEGIN
   pole1=[124.0,31.]
;   pole2=[-100.0,39.]          ;set your own preferred map poles - the pole1
   pole2=pole1                      ;& pole2 arrays allow the user to choose alternating
ENDIF
;
; mirror these values into pole, x range and data range values for each plot
;   in the range 1...nplots
;
poles  = FLTARR(2,nplots)
xrangs = FLTARR(2,nplots)
drangs = FLTARR(2,nplots)
;
; nominal data ranges for various MWFM fields: see FIELD_STRINGS, /LIST for
;   details on the physical quantities and units
;
drang0 = [ [0.,1000.]   $        ;peak vertical displacement amplitudes (m)
      , [0.,10. ]   $        ;Eliassen Palm Fluxes (Pa)
      , [0.,3.0]    $        ;turbulence intensities (J/m^3)
      , [0.,20.]    $        ;peak temperature amplitude (K)
      , [0.,20.]    $        ;peak total horizontal vel. amp. (m/s)
      , [0.,2. ]  ]          ;peak vertical velocity amplitude (m/s)
;
; store poles and ranges for each plot
```

```
;
FOR i = 0,nplots/2-1 DO BEGIN
   poles(0,i*2)     = pole1
   poles(0,(i*2+1)) = pole2
ENDFOR
FOR I = 0,NPLOTS-1 DO BEGIn
   xrangs(0,i) = xrang
   drangs(0,i) = drang0(*, field(i) )
ENDFOR
;
; other plot/data-related default setups....
;
IF NOT KEYWORD_SET(psfile) THEN psfile=1
IF NOT KEYWORD_SET(srcplane) THEN srcplane="
IF NOT KEYWORD_SET(strict18) then strict18=0
IF NOT KEYWORD_SET(map_ann) THEN map_ann=0
IF NOT KEYWORD_SET(plot_items) THEN plot_items=0
;==============================================
;----------------------------------------------
;   create the "what" (what2do) structure
;----------------------------------------------
;==============================================
;

what={                    $
    date:date,            $                ;date string
    source:source,        $                ;atmospheric source string
    grid:grid,            $                ;grid string
    sequence:sequence,    $                ;sequence identifier for source
    special:special,      $                ;special identifier for source
    grib:1,               $                ;use grib format
;    press:[1000.00,925.000,850.000,700.000, $
;    500.000,400.000,300.000,250.000,200.000,150.000,100.000,70.0000, $
;    50.0000,30.0000,20.0000,10.0000] ,  $
;    press:-1 ,           $                ;set to -1 for non-18 levels (e.g., TRMM)
;                                          ;comment out for 18 standard pressures
;                                          ;set to whatever for grib picking of levs
    nazimuths:18,         $                ;# azimuths in ray forecasts
    nkvals:2,             $                ;# horiz. wavenumbers if rayfcst
;    filter:0,            $                ;filter MWFM data?
;    minlz:5.0,           $                ;min. vert wavlgth to filter (km)
;    minlh:100.0,         $                ;min. horz wavglth to filter (km)
;    amp_crit:200.0,      $                ;crit. vdisp for mak_rayini
    latlonlims:latlonlims, $               ;latlonlims array
    only:4,               $                ;orig_wd tag for ridge database
;    units:",             $                ;unit string
;    label:",             $                ;label string
```

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```
      forecast:'0',              $              ;forecast flag
      zerohourforecast:1 ,       $              ;for fh=0 assumes fcst not anal
      nplots:nplots,             $              ;number of plots to do
;      interact:0,               $              ;interactively get vals
      autoscale:1 ,              $              ;automatic color bar scale?
      densscal:1 ,               $              ;1 -> dens-scaled momflux
      colortable:0 ,             $              ;color table to use
      metparam:'z' ,             $              ;overplot what form of data?
;      metlevels:findgen(30)*2+180. , $;use these contour levels
      met_charsize:0.2 ,         $              ;charsize contour met labels
;      snatplot:0 ,              $              ;plot NAT supersaturation
;      nometdata:0 ,             $              ;no met data on plot
      boxes:1,                   $              ;plot ridges as ridge boxes
;      vectors:0 ,               $              ;plot wind vectors?
      field:field ,              $              ;field indices to plot
      levels:levels ,            $              ;level indicies @which to plot
      strict18:strict18 ,        $              ;strict 18 flag
;      batch:0,                  $              ;older batch mode
;      traj:0,                   $              ;older trajectory dump option
;      datadump:1,               $              ;dump data offline or not
;      powerav:2,                $              ;power index 4 offline average
;      xavint:2.5,               $              ;averaging interval (longitude)
;      yavint:2.0,               $              ;averaging interval (latitude)
      poles:poles,              $              ;map poles
      drangs:drangs,            $              ;data ranges (for autoscale=0)
      xrangs:xrangs,            $              ;x map ranges
      giffile:0,                $              ;export a GIF file?
;      gifname:date+'.gif',     $              ;specify gif file name
      psfile:psfile,            $              ;export a PS (postscript) file?
      pstag:'temp'+date,        $              ;character filename for psfile
      colorps:1,                $              ;color postscript?
;      noreverse_pscols:1,      $              ;forces nonreversal of color
      towebsite:0,              $              ;transfer plots to web?
;      webscript:'ToWebSite_Glider', $ ;web transfer script to use
      hardcopy:0,               $              ;print out a hard copy
;      no_flt_trk:1,            $              ;do/don't plot flight track
      srcplane:srcplane  }

RETURN
END
```

Bibliography

Air Combat Command (ACC), Headquarters. Stratospheric Turbulence Fundamental Research Memorandum to Headquarters Air Force Materiel Command 7 March 2002.

Andrews, D., J. Holton, C. Leovy, 1987: *Middle Atmospheric Dynamics*. Academic Press, 489 pp.

Bacmeister, J.T., P. Newman, B. Gary, K. Chan, 1994: An Algorithm for Forecasting Mountain Wave-Related Turbulence in the Stratosphere, *Wea. Forecasting*, **9**, 241-253.

Conover, W.J., 1971: *Practical Nonparametric Statistics*. John Wiley and Sons, Inc., 493 pp.

Dudhia, J., D. Gill, Y. Guo, K. Manning, W. Wang, 2001: PSU/NCAR Mesoscale Modeling System, Tutorial Class Notes and User's Guide: MM5 Modeling System Version 3. [Online at http://www.mmm.ucar.edu/mm5/doc.html]

Durran, D.R., 1986: Mountain Waves. *Mesoscale Meteorology and Forecasting*, P.S. Ray, Ed., American Meteorological Society, 472-492.

Eckermann, S., A. Dornbrack, S. Vosper, and K. Carslaw, 2001: Mesoscale Forecasting of the Stratosphere During SOLVE-THESEO 2000, Unpublished Paper, 7-13.

Eckermann, S., Naval Research Laboratory, Scientist, Washington, D.C., Personal Correspondence, May-December 2002.

Eliassen, A., E. Palm, 1960: On the transfer of energy in stationary mountain waves, *Geofys. Publ.*, **22**, 1-23.

Ellrod, G.P., D.I. Knapp, 1992: An Objective Clear-Air Turbulence Forecasting Technique: Verification and Operational Use, *Wea. Forecasting*, **7**, 150-165.

Geller, M.A., H. Tanaka, D.C. Fritts, 1975: Production of Turbulence in the Vicinity of Critical Levels for Internal Gravity Waves, *J. Atmos. Sci.*, **32**, 2125-2135.

Gill, A.E., 1982: *Atmosphere-Ocean Dynamics*. Academic Press, 662 pp.

Glickman, T.S., et al., 2000: *Glossary of Meteorology*. American Meteorological Society, 855 pp.

Golden J.H., R. Serafin, V. Lally, J. Facundo, 1986: Atmospheric Sounding Systems. *Mesoscale Meteorology and Forecasting*, P.S. Ray, Ed., American Meteorological Society, 50-70.

Grell, G.A., J. Dudhia, and D. Stauffer, 1995: *A Description of the Fifth Generation Penn State/NCAR Mesoscale Model (MM5)*. NCAR Tech. Note TN-398+STR, 122 pp.

Holton, J.R., 1992: *An Introduction to Dynamic Meteorology*. Academic Press, 511 pp.

Hooke, W.H., 1986: Gravity Waves. *Mesoscale Meteorology and Forecasting*, P.S. Ray, Ed., American Meteorological Society, 272-288.

Keller, T.L., 1994: Implications of the Hydrostatic Assumption on Atmospheric Gravity Waves, *J. Atmos. Sci.*, **51**, 1915-1929.

Lindzen, R.S.,1990: *Dynamics in Atmospheric Physics*. Cambridge University Press, 310 pp.

Marks, C.J., and S. Eckermann, 1995: A Three-Dimensional Nonhydrostatic Ray-Tracing Model for Gravity Waves: Formulation and Preliminary Results for the Middle Atmosphere, *J. Atmos. Sci.*, **52**, 1959-1984.

McFarlane, N.A., 1987: The Effect of Orographically Excited Gravity Wave Drag on the General Circulation of the Lower Stratosphere and Troposphere, *J. Atmos. Sci.*, **44**, 1775-1800.

McQuoid, G.J., 51 OSS/OSW, Assistant Superintendent, Osan AB, ROK, Personal Correspondence, October-December 2002.

National Center for Environmental Prediction (NCEP), 2002: EMC Model Documentation. [Available online at http://www.emc.ncep.noaa.gov/ modelinfo/index.html]

Naval Research Laboratory (NRL), 2001: MWFM: Model Description. [Available online at http://uap-www.nrl.navy.mil/dynamics/html/mwfmdesc.html.]

Sinclair, P.C., P.M. Kuhn, 1991. *Infrared Detection of High Altitude Clear Air Turbulence*, NOARL Technical Note 205, pp. 49.

Taylor, J.L., 5RS, Assistant Director of Operations, Osan AB, ROK, Personal Correspondence, December 2002.

Waco, D.E., 1972: Temperature Gradients in Stratospheric Turbulence, *J. Appl. Meteor.*,**11**, 99-107.

Wegiel, J., AFWA/DNXM, Chief, Fine Scale Models Team, Offutt AFB, NE, Personal Correspondence, April 2002.

Whiteman, C.D., 2000: *Mountain Meteorology*. Oxford University Press, 355 pp.

Wilks, D.S., 1995: *Statistical Methods in the Atmospheric Sciences*. Academic Press, 467 pp.

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY) 05-03-2003	2. REPORT TYPE Master's Thesis	3. DATES COVERED (From – To) Jun 2002 – Mar 2003

4. TITLE AND SUBTITLE EVALUATION OF THE MOUNTAIN WAVE FORECAST MODEL'S STRATOSPHERIC TURBULENCE SIMULATIONS	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Allen, Mark S., Captain, USAF	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENP) 2950 Hobson Way, Bldg 640 WPAFB OH 45433-7765	8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GM/ENP/03-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AWFA/DNXT Bruce Telfeyan 106 Peacekeeper Drive Offutt AFB, NE 68113-4039	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

   APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

   EN – Advisor: Lt Col Michael K. Walters

14. ABSTRACT

Stratospheric turbulence (Stratoturb) is a well-known hazard to aircraft in flight. Forecasting mountain waves, specifically the breaking of these waves, is necessary to accurately predict the presence of Stratoturb. The Air Force Weather Agency (AFWA) requested a product with the capability of forecasting Stratoturb at 30, 50, and 70 mb using model data currently available. To facilitate their request, the Mountain Wave Forecast Model (MWFM) was acquired from the Naval Research Laboratory. MWFM turbulence forecasts generated twice daily over East Asia, using the AVN and MM5 models for initialization, were compared to 'S' layer turbulence analyses from the Rawinsonde Observation (RAOB) program, currently used operationally to warn aircrews. Actual verification of the MWFM forecasts was unachievable since in situ turbulence observations were not available, and as a result only subjective assessments of the MWFM's capabilities were possible. The MWFM was determined to be the superior forecast tool based on the temporal and spatial coverage provided when compared to RAOB as well as its promising ability to alleviate the reported overforecasting inherent to the RAOB analyses. Therefore, the MWFM, including code modifications made at AFIT, was recommended for use by AFWA. Further objective analysis of the model's accuracy should be conducted.

15. SUBJECT TERMS

Stratospheric Turbulence, Mountain Wave Forecast Model, gravity wave, MM5, AVN, Rawinsonde Observation program

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Lt Col Michael K. Walters, ENP
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	UU	81	19b. TELEPHONE NUMBER (Include area code) (937) 255-3636, ext 4681